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ATOLL RESEARCH BULLETIN

12. *Preliminary Report on Geology and Marine Environments of Onotoa Atoll, Gilbert Islands*
by PRESTON E. CLOUD, JR.

13. *Preliminary Report on Marine Biology Study of Onotoa Atoll, Gilbert Islands*
by A. H. BANNER *and* J. E. RANDALL

14. *Description of Kayangel Atoll, Palau Islands*
by J. L. GRESSITT

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ACKNOWLEDGEMENT

It is a pleasure to commend the far-sighted policy of the Office of Naval Research, with its emphasis on basic research, as a result of which a grant has made possible the continuation of the Coral Atoll Program of the Pacific Science Board.

It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U. S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs, CIMA, SIM, and ICCP, during the past five years. The Coral Atoll Program is a part of SIM.

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The sole responsibility for all statements made by authors of papers in the Atoll Research Bulletin rests with them, and do not necessarily represent the views of the Pacific Science Board or the editors of the Bulletin.

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NOTICE

The editors of the Atoll Research Bulletin are engaged in compiling bibliographies covering several phases of the science of coral atolls as well as the vegetation of high islands. They will greatly appreciate having any papers mentioning atolls or low coral islands brought to their attention. If readers of the Bulletin care to send in copies of their own papers, this will make it more certain that they will be included in the appropriate bibliographies, and the papers will be available in the Pacific Vegetation Project files for use of those interested. It may be possible, from time to time, to issue reviews of papers that are sent in, especially if they have a direct bearing on the work of the Atoll Research Program, or of the Pacific Vegetation Project.

Such papers should be addressed to:

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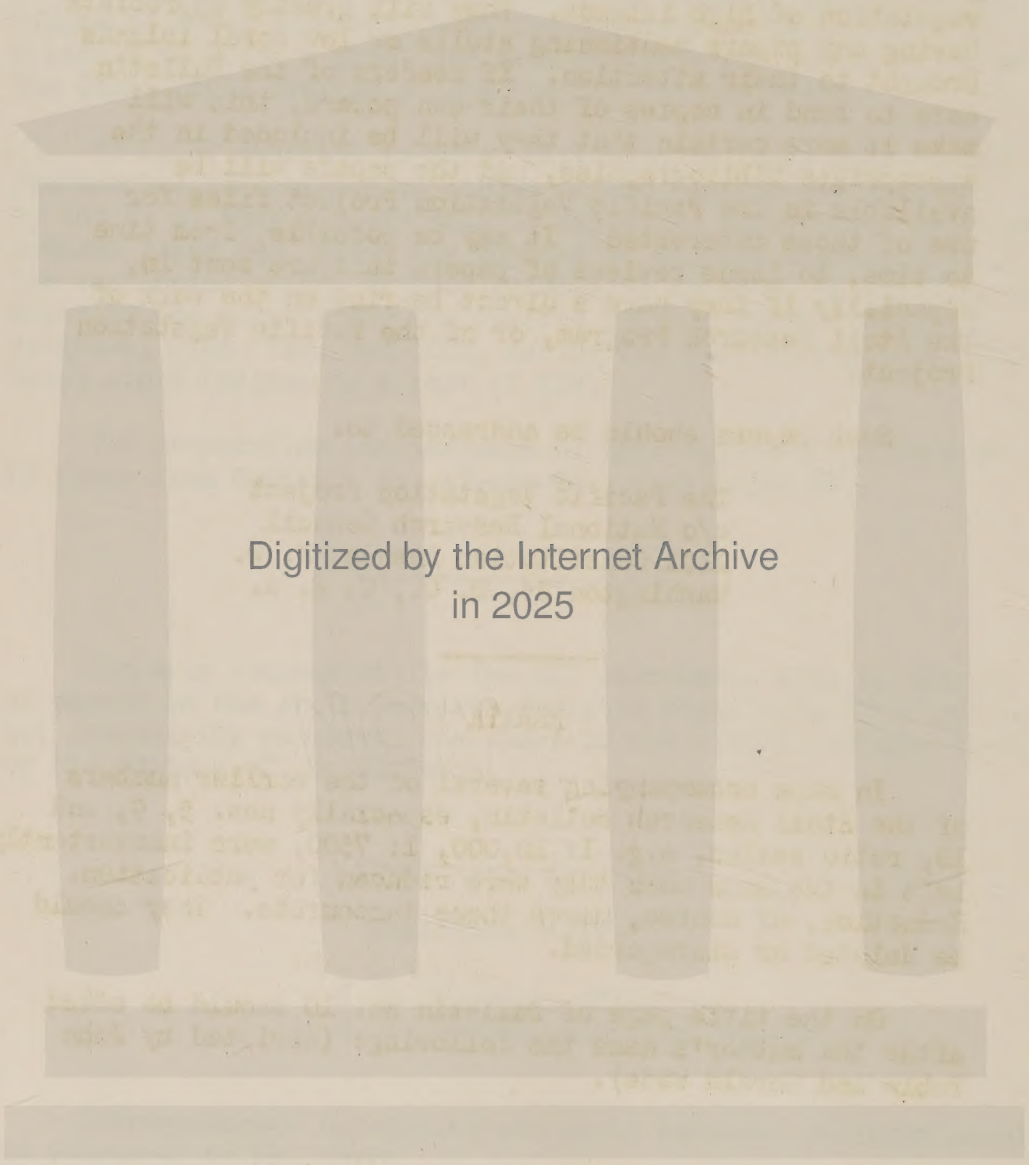
Washington 25, D. C., U. S. A.

ERRATA

In maps accompanying several of the earlier numbers of the Atoll Research Bulletin, especially nos. 5, 9, and 10, ratio scales, e.g. 1: 10,000, 1: 7500, were inadvertently left in the maps when they were reduced for publication. Reduction, of course, makes these inaccurate. They should be deleted or disregarded.

On the title page of Bulletin no. 10 should be added after the author's name the following: (assisted by John Tobin and Gerald Wade).



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No. 12

Preliminary Report on Geology and Marine Environments of Onotoa Atoll, Gilbert Islands

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Preliminary Report on the Geology and Marine Environments of Onotoa Atoll, Gilbert Islands

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

National Research Council

Preston E. Cloud, Jr.
U. S. Geological Survey
Washington, D. C.
June 1952

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This report presents preliminary results of geological field work done in 1951 under the Atoll Project of the National Research Council's Pacific Science Board. The project is supported by funds granted to the National Academy of Sciences by the Office of Naval Research, and the field work was carried out with the active assistance of the U. S. Navy Department, Coast Guard, and Army. Special thanks are due for help received from Mr. Harold Coolidge, Miss Ernestine Akers, and Mrs. Lenore Smith, of the Pacific Science Board, and from Lt. M. E. Katona and Ens. Lee Nehrt, of the U. S. Coast Guard cutter "Nettle." My associates in the field were Dr. E. T. Moul, Dr. W. H. Goodenough, Dr. A. H. Banner, Mr. D. E. Strasburg, and Mr. John Randall.

The field work of the Onotoa Party being in the Gilbert and Ellice Islands Colony, we were the guests of the British Government, then represented by Acting Resident Commissioner R. J. Keegan, who took a most helpful personal interest in our work. Special courtesies and favors were also received from Mr. B. C. Cartland, Mr. Stanley Silver, and Mr. Alan Hart, of the Tarawa Government staff.

The then Colony Lands Commissioner and Administrative Officer on Onotoa, Mr. Richard Turpin, and his wife befriended and helped the entire field party in every conceivable way--to have them as "guardians" was a great help in carrying out our work among a people whose language and ways were remote from ours.

Finally, I must thank the people of Onotoa themselves, who welcomed us to their island and helped us as much as they could.

CONTENTS

	Page
Abstract	6
Introduction	9
General setting and climate	10
Place names	16
General features of the lagoon	18
Principal ecologicaand sedimentary subdivisions	21
Islands	21
Intertidal environments except reefs	23
Outer reef	23
Intertidal to lagoonal environments	25
Environments of the lagoon and leeward shelf	25
Origin of beachrock	28
Hydrology	30
Ground water	30
Shallow sea and tide pools	34
Flow of water over the windward reef	41
Origin of reef-front grooves and surge channels	43
Building and erosion of atoll islands	47
Shifts of sea level and their effects on modern reefs	52
Appendix A - List of reef building corals and hydrozoans	55

Page

Appendix B - Description of sedimentary and ecologic field units ---------- 58

Islands ---------- 58

Dune limesands ---------- 58

Limesands other than known dune deposits 58

Limegravels ---------- 59

Caliche ---------- 60

Land bound areas of permanent brackish water ---------- 60

Intertidal environments except reefs -------- 60

Unconsolidated beach ---------- 60

Rocky beach ---------- 61

Enclosed intertidal flats ---------- 62

Mainly intertidal flats adjacent to lagoon proper ---------- 62

Bars and spits ---------- 64

Outer reef ---------- 64

Intertidal to lagoonal environments --------- 68

Environments of the lagoon and leeward shelf 69

References ---------- 71

ILLUSTRATIONS

Tables

1. Rainfall at Government Station, Onotoa atoll
2. Rainfall at Betio Island, Tarawa atoll
3. Properties of ground water on Onotoa
4. Variations in pH of shallow marine and beach-zone waters
5. Temperature, chloride content, and hardness of shallow marine and beach-zone waters

Figures

1. Index map, showing location of Onotoa
2. Generalized geology and marine environments of Onotoa
3. Island profiles, Onotoa atoll
4. Properties of shallow water in near-shore lagoon
5. Properties of shallow water in flow over windward reef flat
6. Properties of water in low tide pool of windward reef flat
7. Properties of water in high tide pool of seaward beach
8. Temperature and pH of spray pools

PRELIMINARY REPORT ON THE GEOLOGY AND MARINE ENVIRONMENTS OF ONOTOA ATOLL, GILBERT ISLANDS 1/

By Preston E. Cloud, Jr. 2/

1/ Publication authorized by the Director, U. S. Geological Survey.

2/ Geologist, U. S. Geological Survey.

ABSTRACT

Onotoa is a "dry" atoll just south of the equator and west of the international date line. Its yearly rainfall averages only about 40 inches, droughts occur periodically, and ground cover vegetation is sparse. Island deposits are almost exclusively unconsolidated calcium carbonate gravel and sand, the gravel mainly toward the sea and the sand mainly lagoonward. Within this permeable material and the permeable reef-rock beneath, ground water floats in hydrostatic balance with sea water below. Toward the center of islands more than about 1000 feet wide this water is generally potable. In narrower parts of islands, however, it becomes brackish at times of drought, resulting in the death of breadfruit, taro, and even coconut trees. Soils are simply the calcium carbonate sediments, with a humus layer not exceeding about 10 inches and an average pH of about 8.1.

The shape of the lagoon bottom is derived from echo sounding and direct observation. It comprises three shallow basins (maximum depth 8 fathoms) that are separated from one another and from the sea beyond by still shallower water, the whole with numerous small patch reefs that rise to or near the surface. The near-surface framework of the Onotoa reefs consists primarily

of the blue alcyonarian Heliopora, a genus that is not extensively developed there among now living corals. Fish are shown to be important in the production of lagoonal sediments.

The sediments, soils, and surface waters of the island areas of Onotoa, and the ecologic zones and deposits of its shallow marine waters, are here provisionally described and classified. Preliminary identifications of coral collections indicate them to include about 26 genera and 50 to 60 species.

Limited observations on the chemistry and movement of some of the shallow marine waters show a diurnal variation in pH and an out-flowing gravity current across the windward reef flat and upper benched reef slope. During the day pH rises and precipitation of $CaCO_3$ probably occurs in very shallow waters. At night pH falls, favoring solution of $CaCO_3$ in intertidal environments. Dominance of solution effects in the shore zone is believed to result from constant flushing of precipitated products. The out-flowing gravity current is believed an important factor in origin of offshore grooves and surge channels, through abrasion by debris in transit seaward at times of bench truncation.

It is argued that blue-green sediment-binding and lime-precipitating algae are important in formation of beachrock, presumably both through bonding of successive surface layers and through interstitial precipitation of $CaCO_3$.

Atoll islands are built on sufficiently wide reef foundations at or near the surface of the sea at a distance from the reef front determined by local force of storm waves and to a width determined by time and supply of sediment. First a gravel ridge or rampart is erected by storm waves on the reef flat. On the lagoon side of this gravel rampart the sandy portions of the islands

grow by longshore drift of reef flat debris and by wind action. Erosion occurs mainly at times of storm by breaching or complete removal of islands.

Onotoa provides additional evidence in support of the now well-documented 6-foot eustatic fall of sea level that began probably more than 4000 and less than 7000 years ago. The evidence consists of elevated Heliopora flats and elevated cobble stripes such as are known to form only on the reef flat. The superficial appearance of modern reef surfaces in the tropical belt is attributed primarily to whether they were within 6 feet of sea level when this recession began.

INTRODUCTION

This report presents some of the preliminary results of an integrated program of field studies on the terrestrial and marine botany and zoology, geology, and anthropology of Onotoa (Ō nō' tō a), a "dry" atoll in the southern Gilbert Islands (the Kingsmill Group of early records). These studies were made by a field team of the Pacific Science Board during late June, July, and August of 1951.

The Gilbert Islands (fig. 1) straddle the equator just west of the international date line, and the position of the anchorage at the west side and toward the north end of Onotoa was determined by Ens. Lee Nehrt of USCGC "Nettle" as 1°47'33" S., 175°29'30" E. (U. S. Hydrographic Office, 1950, p. 51, states "northwestern end in 1°46' S., 175°30' S."). Onotoa is the most southerly atoll of the group, though two "reef islands" (Tamana and Arorae) lie still farther south.

Operations were carried out from a temporary base camp adjacent to the Government Station on the more northerly of the two main islands of Onotoa (fig. 2). Materials and equipment for camp and technical operations were assembled at Kwajalein and transported to Onotoa by the U. S. Coast Guard Cutter "Nettle," under command of Lt. M. E. Katona.

All botanical names used in this report were supplied by Dr. E. T. Moul and represent either his provisional field identifications or my extensions of them. All titrations for salinity factors were made and computed in the field by Mr. D. E. Strasburg, my assistant in the geologic field studies. Preliminary identifications of corals were provided by Dr. J. W. Wells, of arthropods by Dr. F. A. Chace, and of mollusks by Dr. H. A. Rehder and Mr. R. T. Abbott.

GENERAL SETTING AND CLIMATE

The general setting of Onotoa with reference to currents, winds, and geography is shown in figure 1. This atoll lies between the west-flowing south equatorial current and the east-flowing equatorial countercurrent. A local north-flowing current is suggested by the fact that during our stay there a marked swell from the south produced strong surf on exposed lee reefs that face the south (fig. 2). At the same time surf was weak along the stretch of lee reef north from the anchorage around the north end of the atoll to the large northern island (fig. 2).

According to the map on which figure 1 was based, Onotoa lies at about the northern limit of the southeast trade winds. During late June, July, and August of 1951 the wind blew almost steadily from a little south of east to nearly due east, with the exception of recurrent winds from the west on June 24 and 25 and of occasional squalls from the southeast to south-southeast. On one occasion winds of gale or near-gale velocity blew intermittently from the east and southeast for the better part of a day. The British Colonial Office (1950, p. 39) has reported that "For most of the year there is a steady easterly trade wind, but from October to March...occasional west and northwest gales occur. The wind in these gales does not reach hurricane force." An exception to the rule is found in the record of a hurricane at Butaritari in the northern Gilberts, variously dated as December 1927 and January 1928 (Sachet, in Pac. Sci. Bd ., 1951, pp. 8-9).

The climate of Onotoa is warm and even. For the Colony as a whole, the British Colonial Office (1950, p. 39) reports a temperature range of 80° to 90° by day, with a minimum of 70° at night. Our party maintained no systematic

records of air temperature, but I observed a midday high of 87° to 90° F. between noon and 3 p.m. on several occasions in July and August, and on one occasion the midday temperature stood at a low of 76° F. following a period of gale and near-gale velocity winds. At night the temperature fell into the 70's, to as low as 72° between midnight and 5 a.m.

A summary of rainfall data for the Colony as a whole is given by the British Colonial Office (1950, p. 39) as follows:

> "Rainfall varies considerably, not only between the islands, but also from year to year. In an average year the annual rainfall ranges from 40 inches in the vicinity of the equator to 100 inches in the extreme northern Gilberts, with something around 120 inches in the Ellice Islands. In the Phoenix Islands between 40 and 60 inches is a good year's figure, while the Line Islands' rainfall varies from 30 odd inches at Christmas Island to 150 or more at Washington Island. Ocean Island, the central and southern Gilberts, the Phoenix Islands and Christmas Island are subject to severe droughts lasting many months, when the annual rainfall may fall to less than 20 inches. These droughts are said to have a rough cycle of about seven years. In normal years the wettest months are December to February and the driest from August to October."

About 40 inches may be taken as a round figure for the average annual rainfall of Onotoa. Rainfall records locally available were kept at the Government Station on the northern main island by Gilbertese technicians for 1938 and from January 1944 through August 1951 (table 1). These show an average of 44.2 inches per year. The yearly average for the period 1924 to 1930 was 38 inches, according to E. H. Bryan, Jr. (Pac. Sci. Bd., 1951, p. 2). Available records from 1924 through 1934 led Miss Sachet (Pac. Sci. Bd., 1951, p. 16) to an annual estimate of 34.41 inches. The records of table 1 show 1946 as the wettest year, with 85.1 inches, and 1950 as the driest, with only 6.6 inches.

January averages the wettest month, with 8.6 inches, and October the driest, with 1.3 inches. The wettest month on record was January 1949, with 25.4 inches, and zero rainfall has been recorded for every month in the year except July, August, September, and November. In 1950 no rain at all was recorded from January 1 through June.

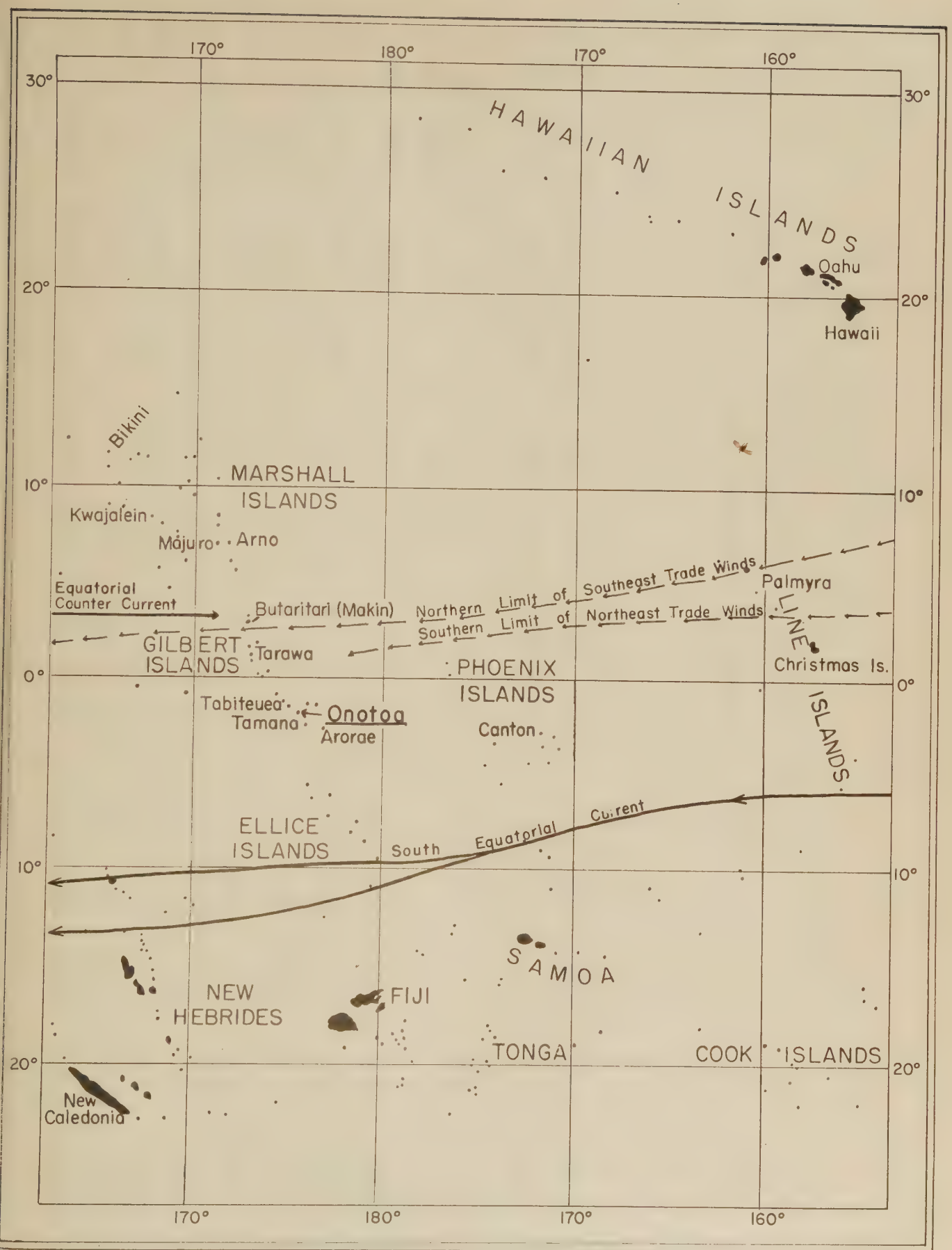


FIGURE I. INDEX MAP, SHOWING LOCATION OF ONOTOA
(From National Geographic Society, map of "Pacific Ocean", Sept. 1943.)

	January	February	March	April	May	June	July	August	September	October	November	December	Total Year
1938	1.18	0.04	1.54	0.13	1.45	1.77	1.87	1.82	3.44	2.81	2.27	0.75	19.1
1944	12.40	0.19	2.73	2.75	0	4.58	3.40	3.09	2.31	0.76	6.10	0	38.3
1945	1.20	0	0.29	1.05	2.88	8.61	5.61	2.59	1.08	0.58	3.50	0	27.4
1946	2.46	2.78	3.93	9.68	6.94	12.53	8.33	8.21	5.94	3.61	1.92	18.76	85.1
1947	16.06	0.23	0.53	0.56	1.22	3.32	0.49	1.26	0.17	0	3.21	3.46	30.5
1948	11.40	20.51	8.62	13.72	7.97	5.42	2.32	1.53	0.95	1.43	3.34	22.29	99.5
1949	25.37	4.85	3.90	0.89	3.76	1.50	2.34	0.98	0.97	0.91	0.23	0.24	45.9
1950	0	0	0	0	0	0	1.80	2.76	0.80	0	0.43	0.77	6.6
1951	7.62	0.50	2.74	2.47	11.99	7.85	12.47	9.35	?	?	?	?	--
Total	77.69	29.10	24.28	31.25	36.21	45.58	38.63	31.59	15.66	10.10	21.00	46.27	352.4
Avg.	8.63	3.23	2.69	3.47	4.01	5.51	4.29	3.51	1.83	1.26	2.62	5.78	44.2

Table 1. Rainfall at Government Station, Onotoa Atoll

(courtesy British Colonial Govt.)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total Year
1946	?	?	?	?.	?	?	13.68	4.22	1.56	5.19	9.28	11.24	---
1947	18.49	3.09	4.33	3.72	9.97	8.19	3.21	2.26	0.81	2.47	4.77	10.83	72.14
1948	21.21	9.35	18.02	15.97	8.43	8.99	6.04	4.69	1.11	1.28	5.31	15.09	115.49
1949	30.04	8.07	11.05	15.96	2.77	2.79	14.74	0.13	2.28	0.36	1.56	1.27	91.02
1950	0.52	0.17	0.15	0.67	0.49	0.49	0.59	3.00	1.20	1.80	2.72	3.73	15.35
1951	9.00	2.24	2.37	8.96	11.51	11.51	10.23	?	?	?	?	?	--
Total	79.26	22.92	35.92	45.28	29.06	31.97	48.49	14.30	6.96	11.10	23.64	42.16	294.00
Avg.	15.85	4.58	7.18	9.06	5.81	6.39	8.08	2.86	1.39	2.22	4.73	8.43	73.50

Table 2. Rainfall at Betio Island, Tarawa Atoll

(courtesy British Colonial Govt.)

In terms of the many characteristically "wet" atolls of the Pacific, where yearly rainfall commonly averages 100 inches or more, Onotoa is truly a "dry" atoll. This, of course, is immediately evident from its sparse ground-cover vegetation. Its climate over a period of years shows no clear division into rainy season and dry season--merely a slight tendency to be drier during September through November and less dry during December, January, and June. This, in turn, suggests only a slight correlation of relative dryness with the season of prevailing easterly trade winds (about late June through November) and of relative "wetness" with the season of more variable winds (about December through early June). Even in the Gilberts Onotoa is relatively dry as compared with an atoll like Tarawa (table 2), which averaged 73.5 inches of rainfall per year from 1947 through 1950.

Statistics for the drought year 1950 at Onotoa and Tarawa are given in tables 1 and 2. At such times the rainfall is insufficient to maintain a fresh-water head, permitting invasion of salt or brackish water through the pervious island sediments and rock foundation. The ground water in the narrower parts of the islands is soon contaminated, with resultant death of breadfruit and eventual death even of coconut trees. Taro too may be adversely affected, although it is ordinarily planted far enough inland to escape the worst effects, and at least one variety found on Onotoa survives in slightly brackish water. To judge from field observations, the only reasonably safe answer to the loss of plant products by drought is to avoid planting breadfruit, coconut, or taro on parts of islands less than 800 feet wide (or, better, 1000 feet wide) and to plant breadfruit not nearer than about 200 feet from standing salt water in any direction.

The effects of drought on ordinary water supply are judged to be less serious than on vegetation. The fluid drunk in largest volume by natives is

green coconut milk, which is self purified. Water for cooking and incidental drinking can be slightly brackish without deleterious effects, and the fresh-water lens of a permeable island area $\frac{1}{4}$ mile or more wide should survive the moderate draft of an endemic island population even during drought periods, especially if washing water is drawn from sources already gone brackish.

PLACE NAMES

The importance that one attaches to the name of a place depends on his perspective. The Gilbertese, living in his atoll universe and dependent on the sea for a living, attaches great significance to the passes in the reef through which he can safely sail his outrigger canoe, to the reefs on which he might wreck it, and to the parcels of ground on which he and his neighbors live and over which they quarrel. He is not interested in names for a whole island or islet, except as it happens that the smaller islets are commonly single parcels of real estate. He does not go to the north or south end of some named island or islet, he goes to some particular named property or to the home of some fellow Onotoan at the village of Temao (Tĕ-mä́-o) or Tekawa (Tĕ-kä́-wȧ).

On figure 2 only a few of the more important place names are given. The names of the seven villages are capitalized. Several islets that coincide with property divisions are indicated by the names of those property divisions in lower case lettering. The few reef names used are indicated by the Gilbertese word for reef, rakai (ra-kī); except for Aon te Baba (ä́n-tĕ-bä-bȧ) and Aon te Rabata (rȧ-bä́-tȧ), to the north and south respectively of the main passage. Aon means on, and te is the definite article, the two together being used in a sort of vernacular sense in combination with the designating name, as we speak of "Smith's place" or "at Joe Webbs" in English. With continued usage such designations take on a sort of formality, and even come to be run together as a single word (like Pittsburg, Beekmantown, Yorkshire, and Aonteuma (ä́n-tĕ-ǘ-ma)).

There is nothing to call the two main islands of Onotoa except the north island and the south island unless names are concocted, and nothing would be

gained by this - the Gilbertese would be bewildered, and Onotoa is already a small enough named subdivision in world geography. The headquarters of the Colonial administrative office on Onotoa is at a place called Buraitan (Bur-i-tan). However, as frequent reference is made to this place and our campsite at its south edge, and as the land areas on the larger islands are not named, it seems easier for the reader to call this place Government Station. For the same reason it seems better that the anchorage be called just that, rather than Komotu (literally anchorage, in Gilbertese).

The authenticity of the names used, as well as the dozens of others not shown on the preliminary map, was checked in the field at every opportunity and finally reviewed on the last day of our sojourn by a group of six "old men" or Unimani (community elders respected for their knowledge) representing five of the seven villages. Because of the close village life and regular habits and travels of the people a man from one part of Onotoa may be quite unfamiliar with names for natural features of other parts of the atoll (the reefs and passes especially), but the concordant judgement of the committee of six would certainly be accepted as final by most Onotoans.

Pronunciation is another problem. To reduce it to its simplest immediately pertinent and practical terms keep in mind that the sound indicated by b is almost that of the letter p, the combination ma sounds like mwa with an almost imperceptible w, the terminal ti is pronounced like an s, and other terminal i's are silent. Rules for syllabification and emphasis are more complicated, but pronunciation is indicated for important words upon their first use in this report.

GENERAL FEATURES OF THE LAGOON

Reference to figure 2 will show the general shape of the Onotoa lagoon bottom as contoured from 21 echo sounding traverses, a few spot soundings, and submarine details visible on air photographs. This chart may not be relied upon in detail for navigation, however. In general, the underwater contour lines refer only to the general depth of bottom between patch reefs. Although a few large patch reefs are individually contoured, no indication is given of the positions of the numerous small reefs that reach to or near the surface over a large part of the lagoon.

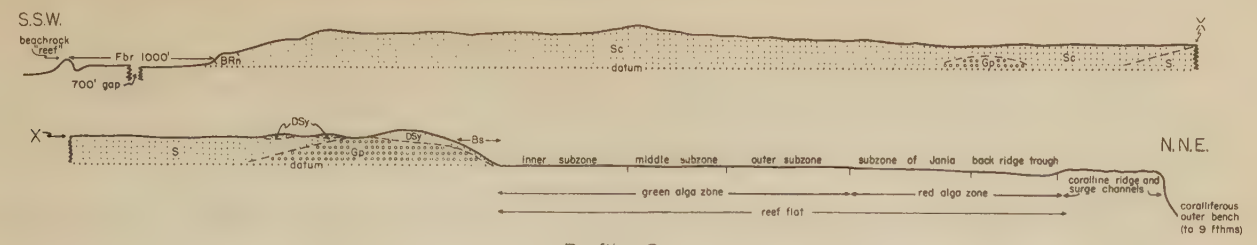
Unless one has learned some particular channel or is completely familiar with the lagoon, he should not attempt to negotiate its waters in any kind of boat (including canoes) without keeping a very sharp lookout for reefs and shoals, and he should avoid travel on the lagoon at night. For ordinary ships' boats the only reasonably clear shore approaches are within the segment defined by lines of fathometer traverses A and 8 to the jetty at Government Station and about along or a little south of the line of traverse G to the Maneaba (Mwa´-ē-a´-ba) at Aiaki (i´-ăk). A course along traverse G would need to evade linear patch reefs between 4000 and 5000 feet offshore, and there is no anchorage for ships off the outer reef here. There are no navigation lights or buoys anywhere, and the only good sighting points are the ends of islands, the white stone monument on Aonteuma, and the churches and large community meeting houses, or Maneabas, shown on figure 2.

The only suitable anchorage for larger vessels at Onotoa is on the leeward shelf outside the gap in the outer reef opposite Government Station. This is a well-protected anchorage except at the rare times of westerly winds. It has a good holding bottom and adequate swinging room. It is reported

(U. S. Hydrographic Office, 1940) that small ships may anchor near "Taburari" (Tȧb-ü-ȧr-ôr-ī) at the south end of the island. However, the only possible anchorage at this place is a very narrow shelf right against the reef and generally swept by a rolling swell from the south--an undesirable anchorage except at times of dead calm. To my knowledge, no vessel of any size has ever entered the Onotoa lagoon. It would be possible, however, by careful manipulation, to work a vessel of less than 9-foot draft into the lagoon and anchor it there, and it might be worth doing if one were to be there beyond a few days. It would also be possible to clear channel and anchorage in the lagoon for regular use by vessels up to 9-foot draft.

The intended reference datum for the depth contours in figure 2 is mean low low tide. This datum can be only roughly approximated, as the U. S. Coast and Geodetic Survey "Tide Tables" for 1951 give no correction factors for Onotoa tides. They do give records for several other Gilbert atolls, and I have arbitrarily assumed the same corrections as for Nonouti (nō-nu̇ch), with Kwajalein as reference point. This gives 6.2 feet as the spring range of tide and 4.4 feet as the mean range of tide. No effort was made to make a precise check on these data, but the assumed ranges and times seemed about right in the field, with considerable local lag in enclosed tide flats and tidal inlets.

Depth traverses were made with Navy Model NK-7 portable echo sounding equipment, which consists of a magnetostrictively actuated transmitter-receiver unit in an outboard wooden fish and a recorder unit that produces a continuous graphic record on a strip of sensitized chart paper. This fathometer was carried in a 20-foot flat-bottomed dinghy driven by a 7-horsepower outboard motor. It was operated by two parallel-connected 6-volt automobile batteries which proved of inadequate capacity to maintain the sensitivity required to operate at depths below 200 feet for more than very short periods.



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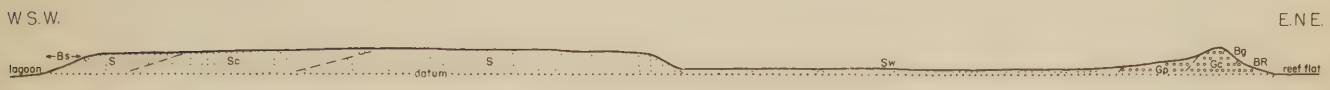

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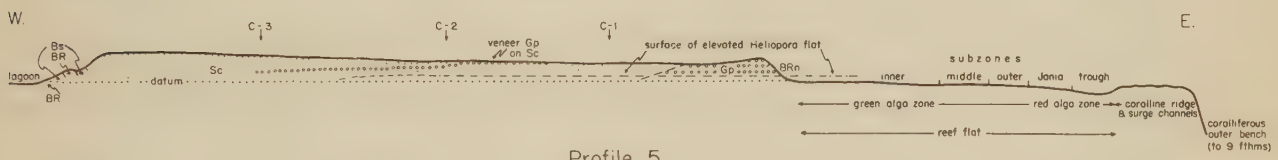

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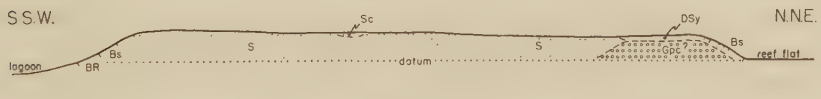

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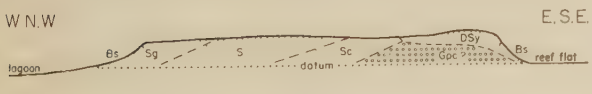

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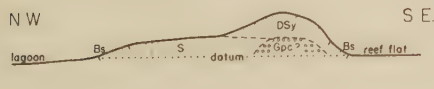

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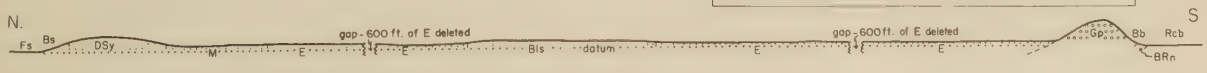

Profile 17

EXPLANATION

Sc	*Calcarina* limesand
S	Undifferentiated limesand
Sw	Limesilt grading to limesand
DSy	Younger dune sand
Gc	Very coarse coralliferous gravel } together
Gp	Coralliferous pebble gravel } designated Gpc
Bs	Sand beach
Bg	Gravel beach
Bb	Boulder beach
BRn	Non-concordant beach rock
BRc	Concordant beach rock
Bls	Bonded limesand
BR	Some combination of BRn, BRc, & Bls
M	Mangrove flat
E	Enclosed tide flat
Fs	Limesand tide flat
Fbr	Beachrock ribbed tide flat
Rcb	Cobble and boulder veneered reef flat
RR	Elevated reef-flat rock
.....	Datum is level of inner edge of reef flat
_____	Highly diagrammatic boundary

FIGURE 3. ISLAND PROFILES, ONOTOA ATOLL

(Vertical exaggeration 5x. Minor and man made irregularities eliminated or generalized. Location shown by number on Figure 2)

A clear record was produced, however, from depths of 200 feet on the outer reef slope into very shoal waters, and, after approximate correction for tide conditions and depth below surface of the transmitter-receiver fish, this record was accepted as the basis for contouring the bottom of the lagoon and upper reef slopes.

Figure 2 shows that the lagoon is very shallow, its maximum depth of 8 fathoms being based on two hand-lead soundings at and near locality C-55. The general bottom topography (excluding the numerous small patch reefs) consists of three shallow basins. The south basin is the largest and deepest, generally deeper than 6 fathoms in its central part and attaining a maximum of 8 fathoms. The central and north basins connect and might be thought of as a single long narrow basin generally exceeding 3 fathoms in depth and attenuated in the middle. The central basin proper exceeds 4 fathoms over a fairly large area and 5 fathoms locally. The north basin has only a small area that is deeper than 4 fathoms. All three basins are separated from one another and from the outer deeps by shelves of 2- to 3-fathom depth. In the passes through the outer reef the depth nowhere much exceeds 2 fathoms. Between the many patch reefs the lagoon bottom is everywhere floored with calcium carbonate sand, silt, or gravel.

PRINCIPAL ECOLOGIC AND SEDIMENTARY SUBDIVISIONS

Systematic studies of the plants and animals, and chemical and mechanical analyses of the sediments and rocks of Onotoa are still in progress. Until these are completed it seems preferable here merely to mention some of the more general or interesting facts and inferences about the principal habitats and deposits of this atoll. As a possible aid to those engaged in comparative studies of atolls, brief descriptions of ecologic and sedimentary units as recognized in the field are given in Appendix B.

Islands

The land area of Onotoa is given by Leonard Mason (In Freeman et al., 1951, p. 274) as 5.2 square miles and the lagoon area as 21 square miles. The land surface is mostly unconsolidated sand and gravel (fig. 2). Solid rock is rare. The sand, gravel, and rock are entirely of calcium carbonate (except for the generally small magnesium content of some algae and shells), a little humus, man-carried debris, and minor amounts of siliceous pumice that has been washed up from distant volcanic eruptions. As they are thus all limesands, limegravels, and limestones, the prefix "lime" (used by geologists to signify $CaCO_3$) should be understood where not actually used in the following pages.

If Onotoa were part of an extensive land area, probably no geologist would make finer distinction of its sediments than that between sand and gravel. Because its land area is small, however, and because details of sediment distribution may be helpful in understanding processes, effort was made to distinguish, and in a general way to map as many different kinds of sediments as could be recognized. For soil classification and vegetation relationships it seems also likely that only a few main types of soils should be recognized:

(1) loose limesands with a well-marked humus layer; (2) loose limesands without a humus layer (younger dune sands); (3) tight-packed, low-lying, generally damp and brackish limesilts and very fine-grained limesands; (4) indurated, phosphatized (?) limesands (old dunes); (5) coarse gravels; and (6) pebble gravels. The properties of the finer pebble gravels at places approach those of the loose limesands, and impinging units ordinarily show gradational relationships.

Soil profiles were run at five localities on loose limesands, at a sixth locality on pebble gravels, and at a seventh on limesilts; and depth of humus was observed at many localities. Tests with a standard Truogg soil testing kit gave a pH of 8.1 for the surface layer of all profiles except that on the damp limesilt, and this had a pH of 8.0. There seemed a slight tendency for pH to increase a little with depth, to as high as 8.3 well below the thin soil layer in fresh parent limesands, but no reading above pH 8.3 was made at any depth. It is difficult, however, to be sure of Truogg index colors as closely as the foregoing suggests, and the difference between 8.0 and 8.3 might be imaginary. Maximum recorded thickness of a well-defined humus layer was 10 inches, but 5 to 8 inches was commoner. At most places in the limesands a zone of slight organic staining extended another 10 to 19 inches beyond the humus layer. Roots were common to depths of 2 to 3 feet and have been encountered at depths as great as 4 feet below the ground surface in freshly dug pits.

As will be brought out by the botanist's report, vegetation zones show a general relation to soil types, especially in certain elements of the ground cover. However, an overriding effect is exercised on vegetative patterns by exposure to wind and salt spray, by the nature of the ground water (related to width of land, distance from sea or lagoon, and height of land), and by artificial factors.

Intertidal environments except reefs

Under intertidal environments are included beach areas, flats that are mainly intertidal, and bars. Reefs, and areas that range from intertidal to lagoonal are considered elsewhere.

The biota of the beaches, tide flats, and bars is generally distinctive. Sand beaches support little in the way of a megafauna--only ghost crabs (Ocypode sp.) and, at some localities on the lagoon side (e.g. C-38), closely packed layers of a small edible pelecypod (Atactodea sp.) an inch or two below the surface of the sand in the mid-tide zone. On rocky beaches, on both seaward amd lagoonward sides, a neritid snail close to Nerita plicata Linné is commonly very abundant, and a high-spired littorinid probably referable to a species of Melaraphe is locally abundant. On rocky and gravelly seaward beaches the common tropical Pacific scavenging crab Grapsus grapsus (Linné) is abundant. Sand bars are very nearly devoid of a megafauna, but burrowing sipunculids may be found. The intertidal flats display a wide biotal variation that will not be discussed here, but some elements of which are noted in Appendix B.

Outer reef

An atoll consists of a ring-shaped outer reef and a central depression or lagoon. In plan view the outer reef is generally irregular in outline and is interrupted and divided into segments by passes. In modern seas islands are commonly located on the reef platform. The lagoon ordinarily contains small patch reefs of a variety of shapes, and, in some places, submarine benches lie beyond the crest of the outer reef. By definition the lagoon of an atoll can contain no pre-existing land, but this would not exclude islands that might be founded on patch reefs. The ring-shaped outer

reef is the essential and most conspicuous feature of an atoll and the subject of the immediate discussion. Patch reefs will be considered under a following section on environments of the lagoon and leeward shelf.

A conspicuous feature of the outer reef, especially in the Gilbert Islands, is the difference between windward and leeward sides. With the exception of Butaritari (or Makin, Mu gin) and Marakei, the atolls of the Gilberts show continuous wave-breaking reef and almost continuous land on their windward (east) sides. Their leeward (west) sides are characterized by irregular outer reefs and few or no islands. All passes into their central lagoons are to leeward. The windward reef flat of Onotoa (also observed parts of Tarawa and Butaritari) is generally exposed at low tide and is veneered with algae. The leeward reefs are commonly submerged for a few feet over most of their area, even at low tide. At many places they show relatively vigorous coral growth--locally even continuous veneers of closely packed living coral. A feature of some Gilbert Island atolls, established for Onotoa but also noted at observed parts of Tarawa and Butaritari, is that at least the upper part of the reef frame was built primarily by the blue coral Heliopora, an alcyonarian, and not a typical stony coral or scleractinian (see also Finckh, 1904, p. 136). That this may be commonly or even generally true for the Gilbert and Ellice Island groups is further suggested by the observations of David and Sweet (1904, pp. 66-70) at Funafuti. Here Heliopora was the frame builder to a depth of 40 feet below high tide in the main bore and occurred in the cores to depths of at least 100 feet.

The ecologic niches of the outer reef may be grouped into those of the reef slope, the reef front (with coralline ridge and surge channels), and the reef flat, the greatest variation being in the reef flat environment.

The relationships of the most persistent recognizable units are shown on figure 3 (profiles 2 and 5)--these being the green alga zone, the red alga zone (including back ridge trough), the coralline ridge, and the benched reef slope of the windward reef.

Intertidal to lagoonal environments

At Onotoa, flats and shoals with extensive growth of the marine grass Thalassia, as well as generally barren rocky flats and shoals, overlap widely from the intertidal to the lagoonal environment and are thus separated from both. Coral veneered rocky shoal bottom is strictly of the shoal lagoon, but it is so closely related to adjacent sparsely coralliferous rocky flats and shoals that it is included with the intertidal to lagoonal environments as a matter of convenience. It is also convenient to include under this heading certain enclosed inlets which, although permanently inundated and similar to the lagoonal units, are separated from the lagoon proper by extensive tide flats.

Environments of the lagoon and leeward shelf

The area here referred to as the leeward shelf is that which extends north and south from the anchorage, beyond the main passage between lagoon and anchorage (see figure 2). Ecologic zones and deposits of the lagoon and leeward shelf may be roughly delimited according to variations in areal importance of patch reefs or veneering coral growth as contrasted with limesand bottom. They may also be further broken down on the basis of differences in the dominating reef-building organisms. The probable nature of the formerly luxuriant growth of Heliopora is well illustrated in the present lagoon by areas of Heliopora patch reefs and limesand.

The effect of certain fish in the production of lagoonal sediments is of special interest. Darwin observed that fish browsed on coral, and Couthouy (1844, p. 97) was aware that lagoonal sediments might "partly arise from the excretions of certain fishes." Safford (1905, p. 90) and Newell et al. (1951, p. 13) also observed fish nibbling on coral, but Finckh (1904, p. 141) states that "although a large number of kinds (of fishes) were watched in the neighborhood of coral, in no instance were they seen to browse on it." There is no doubt, however, that fish do browse on coral, and they probably are important contributors to the sediments around reefs.

The scarids (parrot fish), with their parrot-like jaws, and the acanthurids (surgeon fish), chaetodontids (butterfly fish), and pomacentrids (damsel fish), with their fused comb-like teeth, appear to be primarily browsers on soft algae. Significant to sedimentation is the fact that, in course of feeding, fish from these families scrape off thin layers of the dead calcium carbonate substrate. This was verified by examination of their gut contents. These fish are so numerous and active that they probably produce a fairly constant rain of this fine $CaCO_3$ debris, and, indeed, schools of scarids commonly defecate great clouds of it when startled. In course of time this must represent a considerable contribution to the lagoon sediments.

A coarser sedimentary product is added by the balistids (trigger fish) and monocanthids (file fish), which are armed with a massive dentition of grouped biting teeth, and by the tetraodontids (puffers), which have parrot-like jaws similar to those of the scarids. Their stomachs contain the fresh tip ends of branching corals up to 5 by 10 millimeters and some have yielded chunks of crustacean tests and spines and plates of echinoids, as well as

algae. They have been observed actually to bite off the tips of coral branches, and the fresh pieces of coral in their guts are free of fleshy parts. Doubtless these fish provide a significant part of the coarse fraction of lagoonal sediments.

It is believed that fish are more important in the production and trituration of lagoon sediments than either echinoids or holothurians, the two groups that are most frequently cited as organic sediment producers. In making this argument I mean, of course, to emphasize a commonly neglected or unrecognized factor in lagoonal sedimentation, not to deny the significance of other factors. The calcareous joints of the green alga Halimeda locally bulk large or even dominate in lagoonal sediments (e.g., David and Sweet, 1904, p. 65), and Foraminifera and coralline algae contribute significantly to these sediments through their dead shells and joints. The spicules of gorgonians and other alcyonarians (Carey, 1918, 1931) and the tests of ostracodes are likewise contributing elements. Detrital products strictly due to abrasive wave action and derived from both outer reef and patch reefs also contribute to the lagoonal sediments, but probably do not bulk as large in their overall mass as might be supposed.

The foregoing and other matters related to the ecologic zones and deposits of the lagoon and leeward shelf will be considered more fully and critically when laboratory studies are completed. For the present it must suffice to note that the obvious variations in the shallow lagoonal environment comprise differences in density of concentration of patch reefs. Patch reefs are very abundant and locally almost continuous toward the leeward reefs and passes and gradually decrease in number toward the island mantled windward reef platforms. Linear to irregular areas of bare limesand alter this gradational sequence only locally.

ORIGIN OF BEACHROCK

Beachrock results from lithification of beach debris in the intertidal zone owing to factors not fully understood but apparently peculiar to saline waters that are saturated with calcium carbonate. It is common on tropical sea beaches. It characteristically has the slope and mechanical composition of the constituent beach materials, whatever these may be. Beachrock is mentioned in most reports that discuss the shore-zone geology of tropical islands and has been discussed at length in several papers. A recent summary is by Emery (in Pac. Sci. Board, 1951, p. 34). It is evident that cementation of beach sands to make beachrock results from interstitial precipitation of calcium carbonate in the intertidal zone, but the mechanism of such precipitation is not agreed upon. The ensuing discussion will emphasize the importance of algae in beachrock formation.

Onotoa is an almost ideal laboratory for the study of beachrock, for hard beachrock and bonded limesand occur there over large areas. Bonded limesand, considered to represent incipient beachrock, was found on lagoon beaches, in tide pools and spray pools, and as broad carpets in tide flat areas. It was not found anywhere on the seaward beach at Onotoa. On some tide flats the penetration of fairly solid beachrock by numerous burrows of a small red-clawed fiddler crab (Uca sp.) strongly suggests that the burrows were dug prior to induration of the rock. Everywhere that bonded limesand was found on Onotoa it was observed to be encrusted with living blue-green algae of several genera and species (see descriptions in appendix B). These algae apparently bind the beach and tide flat sands at the surface and, through their biologic activities, may cause or accelerate interstitial precipitation of calcium carbonate beneath. Some samples of the supposed incipient beachrock show successive alga-capped layers or laminae, and it

looks very much as though the algae play the important function of holding the sands in place until they can be indurated.

I am satisfied that the formation of beachrock in protected localities is brought about by, or greatly accelerated by, the activities of blue-green algae and hope to document this fact more fully in a later report. It is difficult, however, to see how ordinary blue-green algae could have a significant effect on the bonding of conglomerate beachrock on an exposed seaward beach. Perhaps the answer is that beachrock does not form on exposed beaches except in protected places or during times when wave action is very weak. A sample of firmly bonded gravelly sand containing numerous brass cartridge shells was collected on a seaward beach at Tarawa, but this had formed in a pocket behind ledges of older beachrock and was encrusted and ramified with soft algae. If any given locality were free from strong wave action only long enough for algal bonding of beach detritus to get a good start, cementation might continue when the locality again was exposed to more vigorous wave attack.

HYDROLOGY

Hydrologic observations made were limited by time, facilities, and staff. Several samples of ground water and one sample of sea water were taken for chemical analysis (not completed); some observations of movement of dyed water across and beyond the windward reef were made; and diurnal variation of pH, temperature, and chloride ion concentration was observed at selected localities. In addition, some determinations were made of total hardness, calcium hardness, and magnesium hardness, all "as $CaCO_3$," and of calcium and magnesium ion concentrations. Chloride was determined by titrating with silver nitrate and potassium chromate, and hardness factors were determined with stock hardness indicators and sodium hydroxide as described by D. L. Cox (Pac. Sci. Bd., 1951, pp. 22-26). Observations of pH were started with a Gamma electric meter using glass and calomel electrodes, but, owing to battery failure, it was necessary to complete this study with a Japanese-made (Mitamura) set of colorimetric indicators. Colorimetric indicators, unfortunately, are neither as reliable nor as finely calibrated as the electric meter.

In the ensuing discussion the term "chlorinity" refers to the concentration of the chloride ion (Cl^-) in parts per million of solution.

Ground water

Ground water in the permeable medium of an atoll island occurs as a lens of fresh water floating in hydrostatic balance on salt water below. As fresh and salt water are miscible, a zone of mixing occurs at the contact of the fresh-water lens with the salt water below. Various irregularities in the shape and integrity of the lens may result from openings, passageways, or

variations in permeability of the island foundation that accelerate or retard mixing. A ground water lens of this sort is called the Ghyben-Herzberg lens, after two of its early propounders, and it is succinctly discussed by Wentworth (1947).

The source of fresh water in the lens is rain. Given adequate rain and unvarying permeability, the thickness of the lens depends on its areal dimensions and the amount of loss through evaporation or artificial draft. As a result of the difference in density between about 1.000 for fresh water and about 1.025 for sea water, the thickness of the balanced lens, assuming no mixing, should be 40 times the height to which the balanced fresh water extends above sea level. In small islands or very narrow parts of long ones the fresh-water lens will be relatively thin and brackish. In large islands of medium and consistent permeability, assuming adequate rain, the lens will be thick and the water potable. In time of drought this fresh water, in parts of islands wide enough to have a reasonably thick lens, would be lost only slowly by diffusion, mixing, and outflow. Heavy draft without recharge, however, leads to salt-water invasion.

Ample demonstration that the ground water of Onotoa comprises a lens of the Ghyben-Herzberg type is provided by observed diurnal variations of the level of ground water at site C-2 (center of island, shower well at camp). This level fluctuated through 16½ inches with a tide range at the time of about 4.3 to 5.5 feet, and its high and low stands followed the high and low tides with a lag of 2 to 3¼ hours. Obviously, the fresh water is affected by the tides and must be floating on interstitial sea water in the permeable sediments and rocks beneath.

Eight ground water samples were studied from an area about ¼ mile square and centering on the Government Station and our campsite (figs. 2, 3). This

area was selected for study partly as a matter of convenience and partly because the island at this place approaches the probable minimum width (1000 to 1400 feet) required to maintain a fresh-water lens continuously through drought periods of recorded duration.

Results of field tests on this ground water are given in table 3. Samples 1 to 5 were from wells dug and maintained prior to the arrival of the American field party. Sites C-1, C-2, and C-3 (fig. 3) were dug mainly to obtain ground water samples and geologic sections at regular intervals across the island. Sites 1, 2, 3, 5, and C-2 were about at the center of the island, whereas sites 4 and C-3 were halfway from center to lagoon beach, and C-1 was halfway from center to seaward beach. Of the five wells tested, the two--1 and 2--that showed lowest chloride concentrations and total hardness were at the center of the island, but one well toward the lagoon beach (4) provided potable water. Well 3, relatively high in chloride content, total hardness, and magnesium, and not good for drinking was also at the center of the island and only 225 feet south of well 2, a good well. The data of table 3, in combination with taste tests of other wells, indicate that a well toward the center of parts of the larger islands that are wider than about 1000 feet has a good chance of producing a fairly continuous supply of potable ground water under the normal draft of the native population. Wells in narrower land or near the beach are apt to be brackish. According to the principles of hydrostatic balance in the Ghyben-Herzberg lens, as the land is wider, the lens is thicker, and the chances of a sustained supply of potable water are better.

Irregularities in fresh-salt boundary relationships in the lens due to openings in the reef-rock foundation are to be expected, and the relatively

Well or site	pH Gamma meter	pH phenol red dye	pH thymol blue paper	Chloride (ppm)	Total hardness as $CaCO_3$ (ppm)	Ca^{++} (ppm)	Mg^{++} (ppm)	Temp. ° C
1	7.66	—	7.5	262	418	98	42	29
2	7.98	—	—	264	429	70	62	29
3	7.40	—	7.7	989	693	93	112	28
4	—	7.7	—	633	532	75	84	26
5	—	7.7	—	640	548	88	80	26
C-1	7.48	—	—	—	—	—	—	23
C-2	—	7.5	—	—	—	—	—	23
C-3	—	—	7.7	—	—	—	—	—

Table 3. Properties of ground water on Onotoa

(Note that all pH readings were made during daylight hours, pH of wells with algae should fall at night)

high chloride and magnesium content of well 3 is possibly due to such an opening or passage. It is possible to predict the location of such openings only by methods that are prohibitively expensive with reference to the ease and cheapness of digging a shallow well. The practical way of meeting the problem of ground water supply in the Gilberts is to locate wells intended to supply drinking and cooking water at or toward the middle of islands more than 1000 feet wide and at least several thousand feet long. Some wells so located will encounter brackish water in any event, but they should be proportionately few.

Shallow sea and tide pools

Observations were made on diurnal variation of pH and temperature of water from a high tide pool and a spray pool on the windward sea beach, from a tide pool on the windward reef flat, from flow over the reef flat, from immediately offshore in the shallow lagoon, and from a spray pool with bonded limesand on the lagoon beach. The last mentioned, though a spray pool at neap tides, is a tide pool at times of spring tide. All sites observed were adjacent to the field camp south of the Government Station on the northern main island. In addition to pH and temperature, the concentration of calcium, magnesium, and chloride in parts per million was determined.

The beach zone pools at Onotoa mostly have flat bottoms, a large population of fixed algae, and a few snails (Nerita) and blennies. The tide pools of the inner reef flat have smooth, shallow, rounded bottoms, commonly elongated normal to the shore and with algae growing between rather than in them. The beach zone pools are considered primarily attributable to solution. The reef flat pools are probably in part abrasion features. Emery (1946) gives results of similar but more complete studies of tide pools at La Jolla, California, and provides references to previous publications on the subject.

The results of the observations at Onotoa are shown graphically in figures 4 to 8, and critical variations in hydrogen ion concentration are summarized in table 4. From these data it is clear that, excluding extraneous factors such as affected the high seaward tide pool of figure 7, temperature, chlorinity, and pH all show the same general pattern of diurnal variation. This pattern is a recumbent sigmoidal curve, rising to a peak during the day and falling to a low at night. Moreover, samples tested for Ca^{++} and Mg^{++} show that these properties vary directly with chlorinity.

The batteries of the electric pH meter gave out toward the end of the first set of 24-hour readings, but sealed water samples had been taken for all hours read and these samples were immediately checked with a Japanese-made (Mitamura) set of fluid and paper colorimetric indicators. These indicators showed consistent results following a diurnal variation curve similar to that of the electric meter but generally reading 0.3 to 0.5 unit higher and tending to flatten the curve slightly toward the peak. This check makes credible the general range of readings subsequently made with the colorimetric indicators, but also suggests that the colorimetric curve should be scaled somewhat lower than it actually reads.

Data from the shallow lagoon (fig. 4) and water in flow over the windward reef flat (fig. 5) may be taken as an approximate measure of the limits of normal variation in the very shallow marine waters of Onotoa. These show a range in chlorinity of 18,080 ppm Cl^- just before daybreak to 20,680 ppm Cl^- during the day. The pH (meter measured) ranges from 7.63 at midnight or early morning hours to 8.80 in midafternoon, and temperature ranges from 23.5° C just before daybreak to 34° C at midday. The lowest pH recorded electrically was 7.63 for water in flow from beyond the outer reef over the reef flat at midnight, and the highest was 9.05 for water in a then stagnant reef flat tide pool at midtide and midafternoon. This range is close to the range found

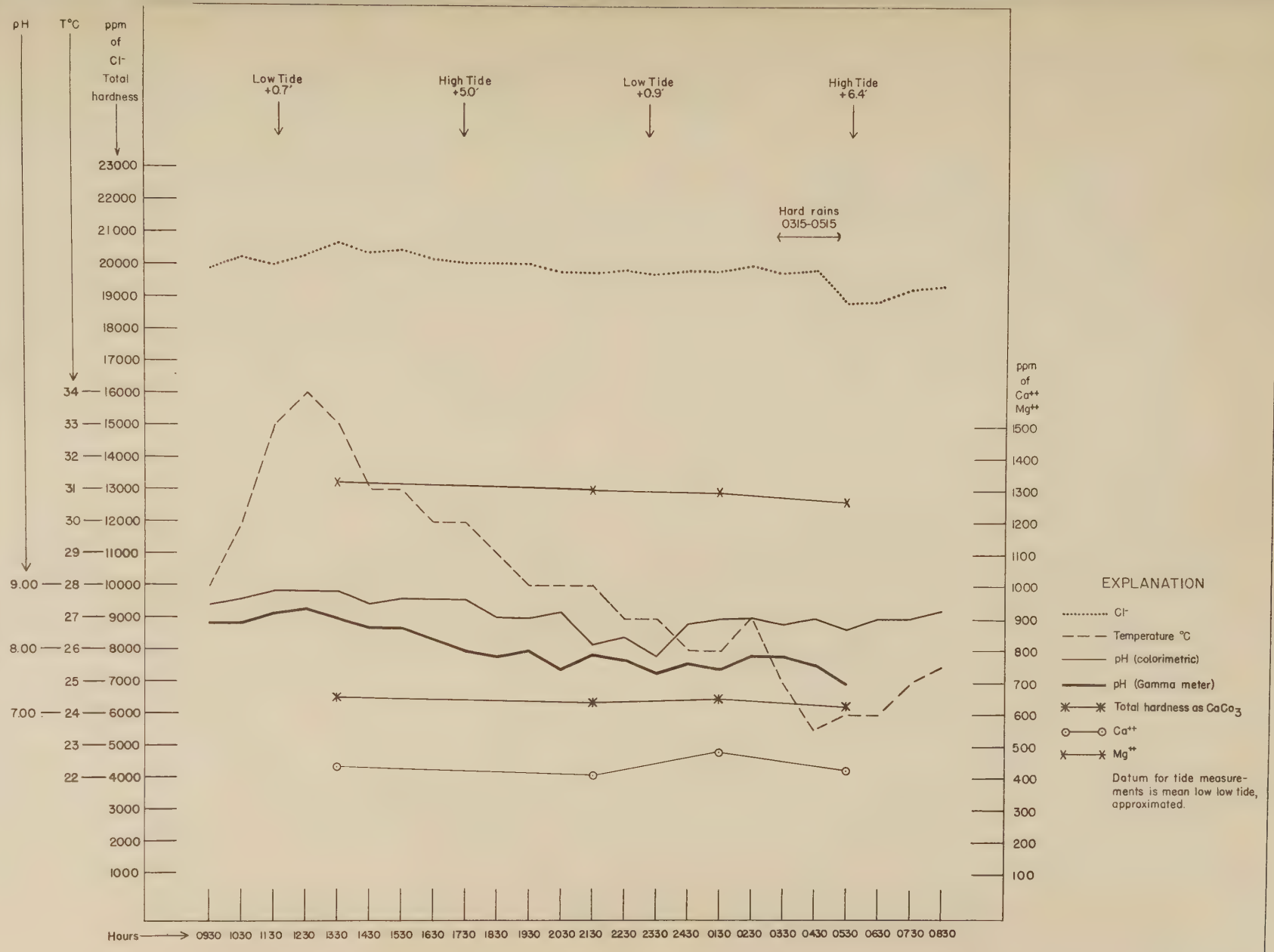

FIGURE 4. PROPERTIES OF SHALLOW WATER IN NEAR SHORE LAGOON (JULY 6-7, 1951)

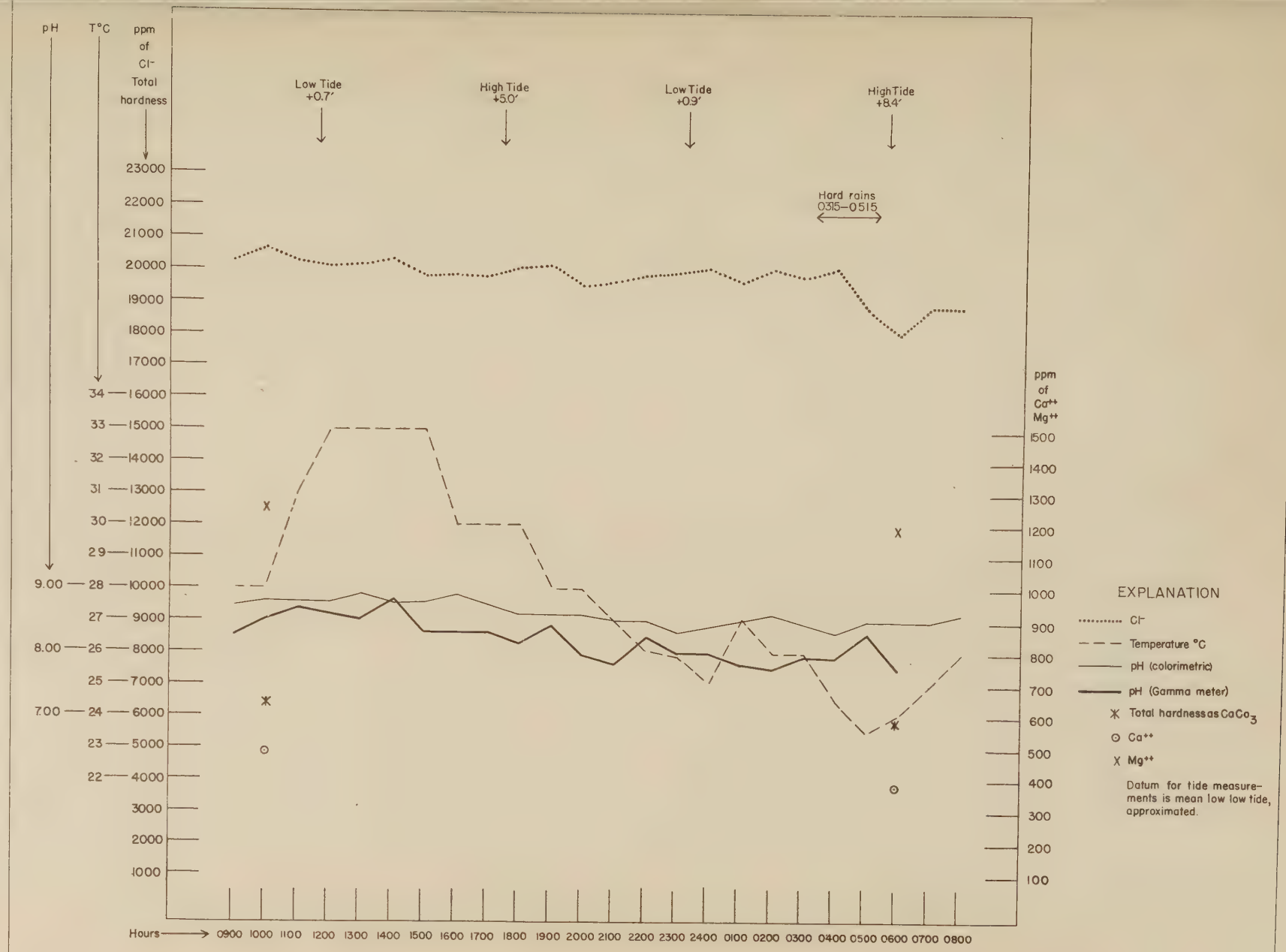

FIGURE 5. PROPERTIES OF SHALLOW WATER IN FLOW OVER WINDWARD REEF FLAT (JULY 6-7, 1951)

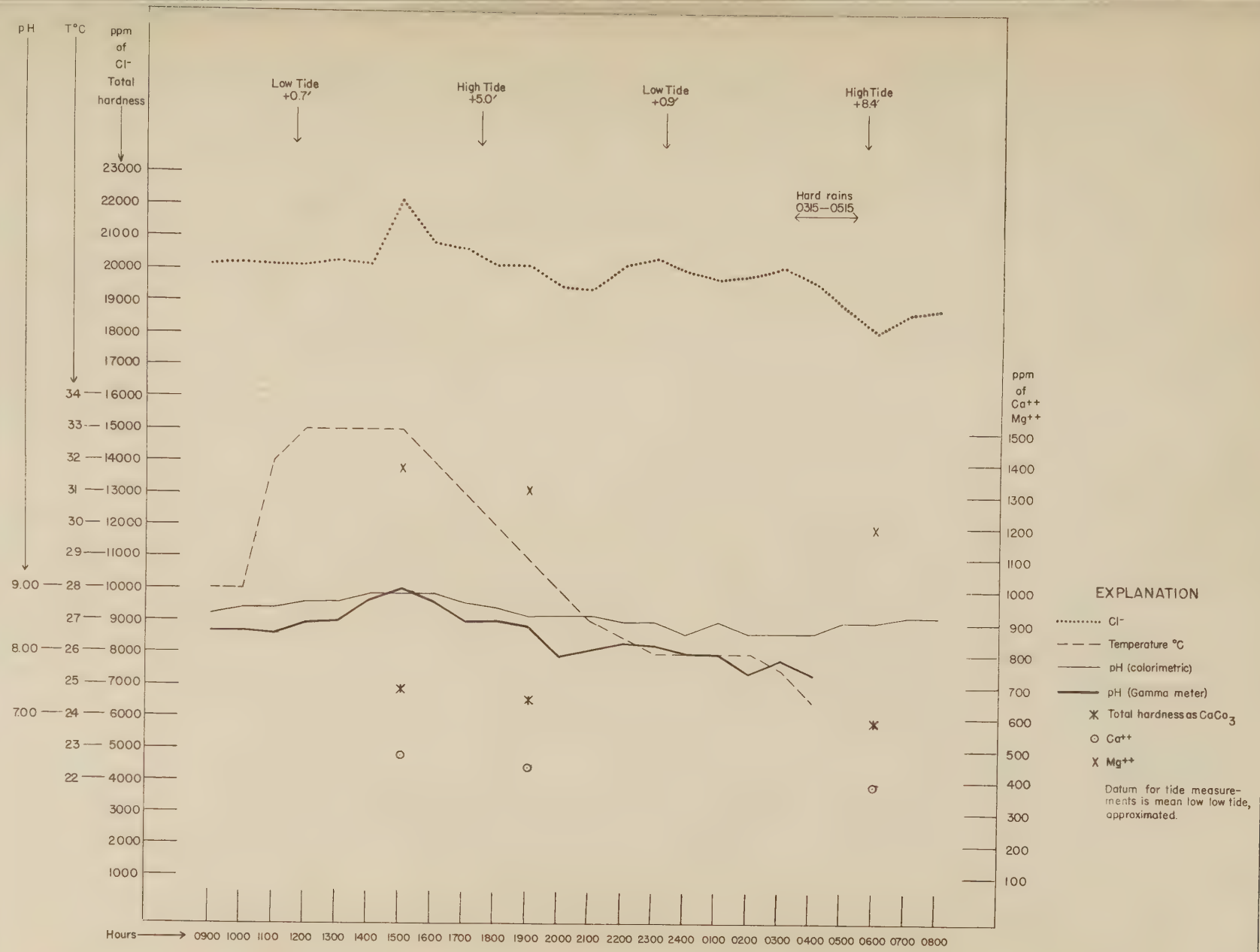

FIGURE 6. PROPERTIES OF WATER IN LOW TIDE POOL OF WINDWARD REEF FLAT (JULY 6–7, 1951)

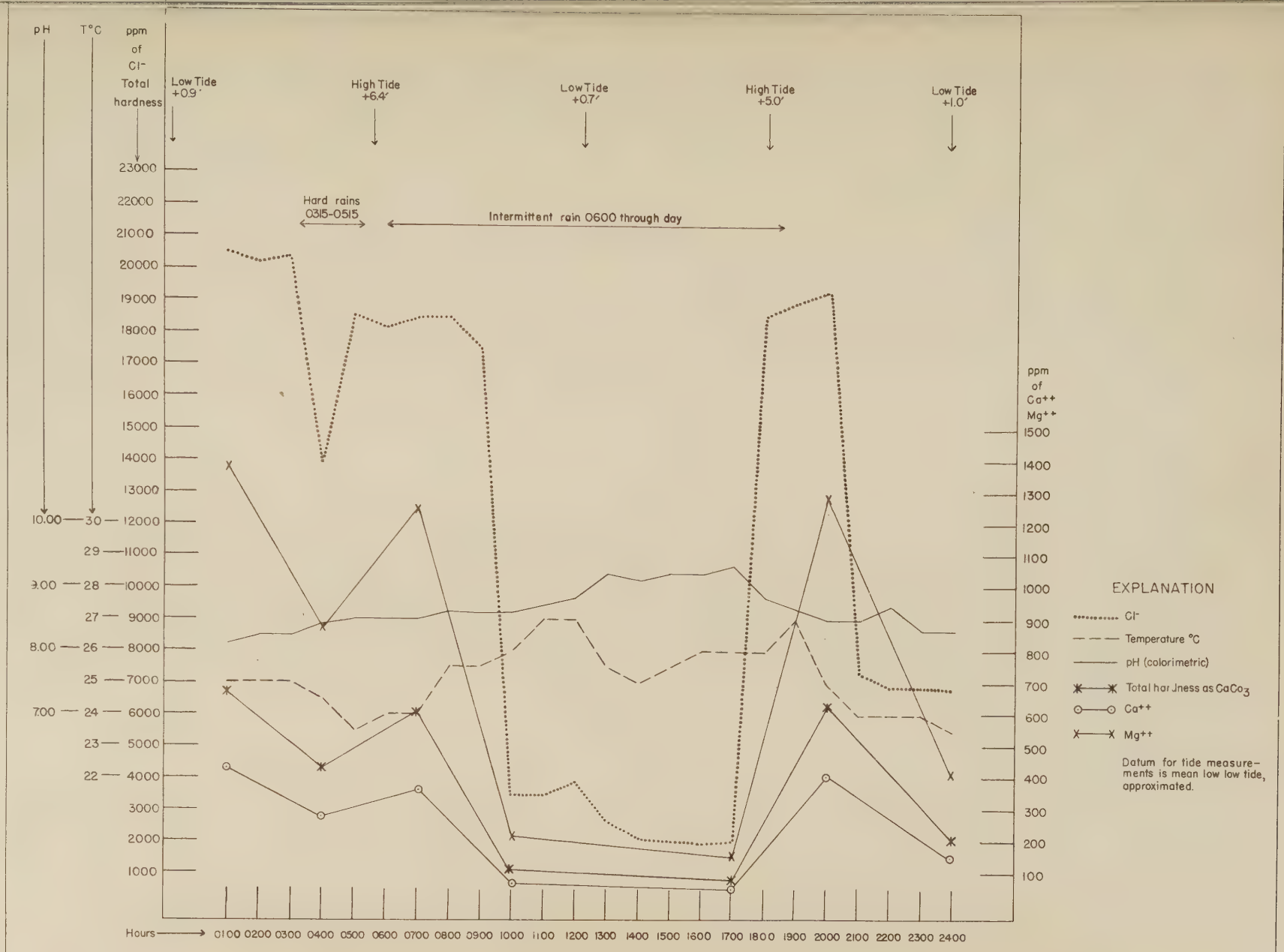

FIGURE 7. PROPERTIES OF WATER IN HIGH TIDE POOL OF SEAWARD BEACH AREA (JULY 7, 1951)

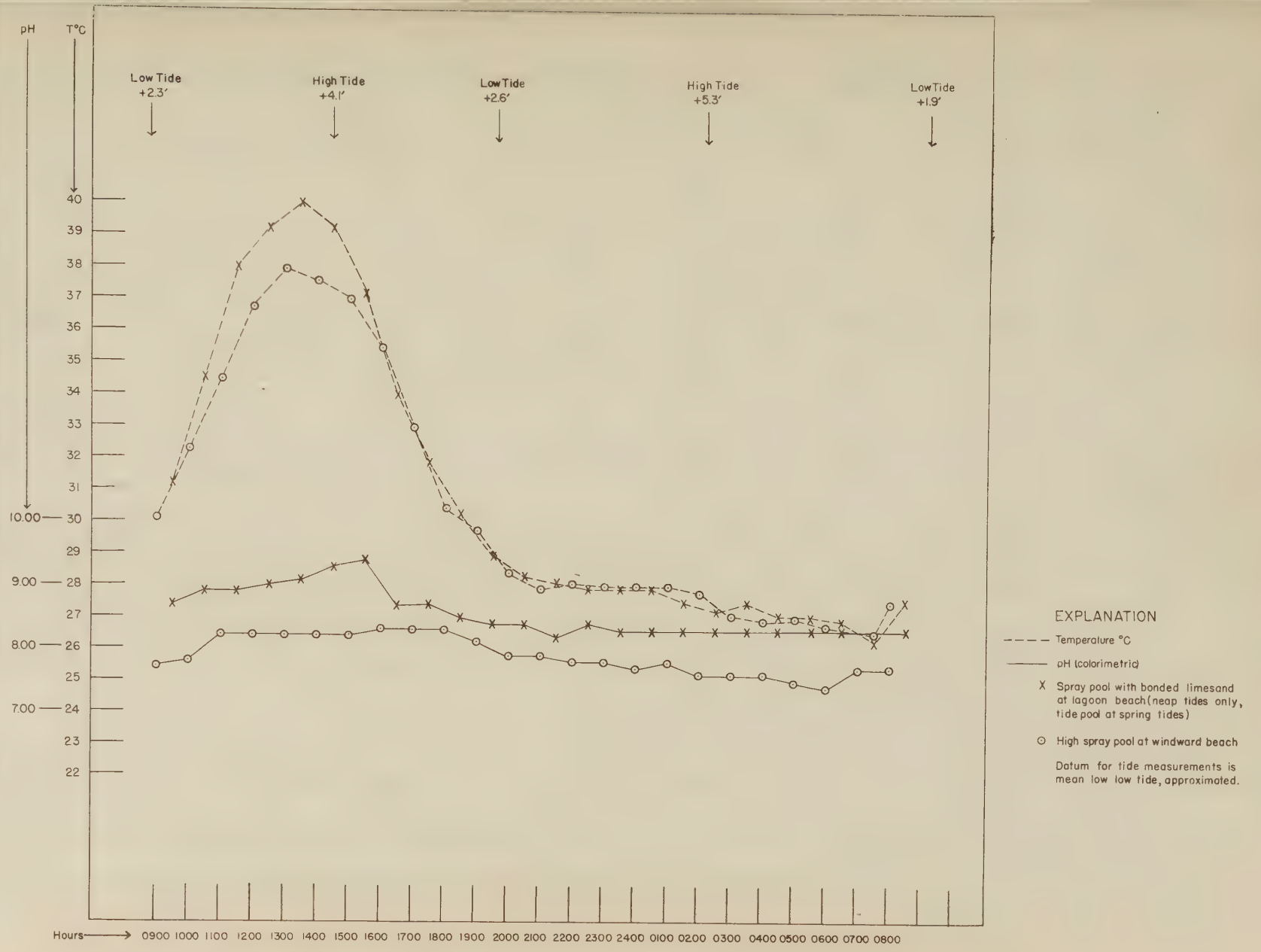

FIGURE 8. TEMPERATURE AND pH OF SPRAY POOLS (AUGUST 27-28, 1951)

Sample and figure reference	Minimum pH				Maximum pH				Periodic variations of pH							
									high				low			
	meter		colori-metric		meter		colori-metric		meter		colori-metric		meter		colori-metric	
	pH	time	pH	time	pH	time	pH	time	pH	time	pH	time	pH	time	pH	time
Shallow lagoon, fig. 4	7.63	2330	7.9	2330	8.63	1230	8.9	1130 to 1330	>8.0	0500 to 1900	>8.5	0800 to 2000	<8.0	2000 to 0400	<8.6	2100 to 0700
Windward reef, fig. 5	7.75	0200	8.3	2300 and 0400	8.80	1400	8.9	1300 and 1600	>8.0	0930 to 1630	>8.5	0830 to 1730	<8.0	1730 to 0530	<8.6	1830 to 0730
Low windward tide pool, fig. 6	7.65	0200 and 0400	8.3	2400 and 02-0400	9.05	1500	8.9	1400 to 1600	>8.2	0500 to 1900	>8.5	0700 to 2100	<8.2	2000 to 0400	<8.6	2200 to 0600
High windward tide pool, fig. 7	—	—	8.1	0100	—	—	9.3	1700	—	—	>8.4	0500 to 2200	—	—	<8.5	2300 to 0400
Windward spray pool (*), fig.8	—	—	7.4	0600	—	—	8.3	1600 to 1800	—	—	>8.0	1100 to 1900	—	—	<8.0	2000 to 1000
Lagoon (leeward) spray pool, fig.8	—	—	8.2	2130	—	—	9.4	1530	—	—	>8.3	0930 to 2030	—	—	<8.4	2130 to 0830

(*) Presence of decaying flesh in pool inferred to account for low pH readings.

Table 4. Variations in pH of shallow marine and beach zone waters

Sample and figure reference	Temperature °C				Chloride (ppm)				Hardness (ppm)		
	min.	time	max.	time	min.	time	max.	time	total hardness	Ca^{++}	Mg^{++}
Shallow lagoon, fig. 4	23.5	0430	34.0	1230	18,880	0530	20,680	1330	6225 to 6530	408 to 486	1266 to 1317
Windward reef, fig. 5	23.5	0500	33.0	1200 to 1500	18,080	0600	20,680	1000	5855 to 6375	380 to 486	1192 to 1254
Low windward tide pool, fig. 6	23.5	0500	33.0	1200 to 1500	18,080	0600	22,120 20,880	1500 1600	5855 to 6855	380 to 478	1192 to 1375
High windward tide pool, fig. 7	23.5	0500 and 2400	27.0	1100 1200 1900	1960	1600	20,480	0100	735 to 6685	46 to 422	151 to 1368
Windward spray pool, fig. 8	26.6	0700	37.9	1300	—	—	—	—	—	—	—
Lagoon (leeward) spray pool, fig.8	26.3	0730	40.0	1330	—	—	—	—	—	—	—

Table 5. Temperature, chloride content, and hardness of shallow marine and beach zone waters

by Emery (1946, p. 221, fig. 12) in a southern California tide pool with a temperature range of 14° to 26° C. A pH reading as low as 7.4 was recorded colorimetrically in a high windward spray pool at 6 a.m. and one as high as 9.4 in a lagoonside spray pool at 3:30 p.m.

Importance is attached to figure 7, representing a high seaward tide pool, because it shows an essentially regular diurnal variation curve of pH (colorimetric) through a period of fluctuating temperatures and dilution by rain (2.05 inches rainfall in 24 hour interval recorded on figure 7). Concentration of Cl^- in this tide pool fell 6000 ppm during hard rains from 3:15 to 5:15 a.m. However, it jumped back 4500 ppm with the first flushing wave of the high tide after the rains stopped and was kept at this concentration as long as the tide pool was reached by an occasional high wave. Concentration fell 15,000 ppm during a day of rains but jumped from 2,000 to 19,000 ppm as the tide reached peak and flushed the pool again. Chlorinity fell off markedly again at 9 p.m. as the tide receded and the pool was beyond reach of waves, but this drop must be explained by dilution from accumulated rain water seeping and trickling down from the irregular rock surface above the pool, for there was no rain at this time. Concentration in ppm of $CaCO_3$, $MgCO_3$, Ca^{++}, and Mg^{++} varied directly with Cl^-, and none of these concentrations showed any relation to temperature of pH.

Clearly, the pH of this tide pool is not significantly affected by or related to either temperature, chlorinity, or any of the variables that change with chlorinity. However, pH, temperature, and chlorinity do vary together in other situations (figs. 4 - 6, 8), and it looks as if they may vary in relation to some common factor. Sunlight provides a suitable common factor for temperature and pH, but its possible relation to the measured variations in chlorinity is not clear. Rain and variation in outflow from the fresh water lens with the tides are probably more important in accounting for chlorinity variations.

The general periodic variations of pH from relatively high during the day to relatively low at night is well brought out by table 4. During hours of sunlight marine plants (both attached and planktonic) use up CO_2 in photosynthesis, causing relative acidity, as measured by hydrogen ion concentration, to decrease, and pH, the inverse measure of hydrogen ion concentration, to rise. The reverse is true at night, when plants are not using CO_2 for photosynthesis, but both plants and animals are producing CO_2 through respiration. The CO_2 content of the water increases, hydrogen ion concentration rises, and pH falls. This is true of the high seaward tide pool, without regard to the extraneous factors that affect chlorinity and temperature, presumably because the variation in pH is organically controlled. Emery (1946, p. 221, fig. 2) clearly shows that diurnal variation of pH in tide pools at La Jolla is inversely related to CO_2 concentration. At the same place, he notes that variations in partial pressure of CO_2 from greater than in air at night to less than in air during the day indicate a larger range in CO_2 actually released and used than is indicated by measurements obtained.

Special interest in the diurnal cycle of pH variation derives from the part that tropical marine waters appear to play in solution and precipitation of $CaCO_3$. On the one hand, it is now common knowledge that such waters are normally saturated or supersaturated with $CaCO_3$ and therefore not capable of taking it into solution. On the other hand, the physical evidence of pitting and undercutting of tropical limestone shores is convincing to some (including myself) that normal tropical marine waters, under some conditions, can dissolve $CaCO_3$. Data obtained at Onotoa substantiate the conclusion already reached by Emery (1946, pp. 225-226) that these conditions are related to diurnal variation of pH in intertidal or very shallow waters with a high biotic density. During the day, CO_2 in shallow waters and tide pools is

being used in photosynthesis, pH rises toward a maximum of 8.6 to 8.8 or 8.9[3/] in open shoal water and 9.1 to 9.4[3/] in tide pools and spray pools, and precipitation of $CaCO_3$ should take place. At night, when the CO_2 content of these same waters is increasing, pH falls toward a minimum of 7.6 to 8.3[3/] in

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[3/] Highest readings colorimetric and probably in the range of 0.3 high.

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both open shoal water and tide pools, and it is probably at times of lowering of pH below about 7.8 to 8.0 that solution occurs. Emery (1946, pp. 222-225) has made the necessary calculations to show for similar data, though in a temperature range about 10° C lower, that solution at night and precipitation during the day is in fact possible within the observed range of pH. In arriving at the foregoing figures, data from the windward spray pool of figure 8 are discounted, because this pool was found to contain decaying flesh that doubtless accounts for its low pH. Of course, such things are common in tide pools and spray pools and would account for accelerated solution there.

That the effects of solution in shore zone areas are commonly more in evidence than precipitation is explained by the susceptibility of the minute aragonitic needles of the precipitated $CaCO_3$ to being flushed away by waves--or even blown away by wind at low tide from parts of the reef and tide flats that are exposed long enough to dry. Precipitated $CaCO_3$ in and near the shore zone of Onotoa appears to be preserved only on the elevated rims of certain tide pools and probably as part of the white encrustations on the surfaces of sediment-binding algae. Naturally, rain water, both as solvent and as flushing medium, accentuates the process of pitting and formation of tide pools and spray pools, and the effect of decaying organic matter is also important. However, neither rain nor decaying organic matter can have much

effect on the production of the undercut notches that are so common around limestone islands of the tropical seas.

Flow of water over the windward reef

The movement of powdered fluorescein marker dye was observed at several places over the reef flat, in surge channels, and over the benched reef slope seaward of the reef front along the windward shore near Government Station. Observations were made during a receding tide at a time of moderately strong surf, and all time intervals and quantities of dye were estimated.

About midway of the reef flat, which is about 800 feet wide here, a patch of dye about 20 feet in diameter on application spread out to about 80 feet wide by 100 feet long (elongated normal to shore) and moved altogether past the point of application in about 30 seconds. It then surged inward and outward with onshore surge and recession of waves but sinking as it moved and with dominant movement seaward along the bottom. Within about 10 minutes after application the dye was foaming in the surge channels of the coralline ridge.

About half a cupful of the powdered dye was applied just behind the coralline ridge and then observed from a raft anchored about 110 feet beyond the ridge on the benched reef slope. Traces of this dye foamed in the upper waters of the surge channels for a long while, but the bulk of it continued to sink and drift seaward for about 30 minutes. It gradually worked down to a basal layer of water and streamed out over the seaward sloping bench.

Dye was added to surface water about 50 feet seaward of the coralline ridge and surge channels. This dye worked outward and downward, streaming to the bottom at about a 30° angle in about 5 minutes. Within about 15 minutes it was all seaward of the shelf.

About three-quarters of a cupful of powdered dye was released at the bottom of a 6- to 8-foot-wide surge channel near its midlength, in about 10 feet of water. This dye surged up and down and spread to adjacent grooves, but it stayed in the surging waters for about 10 to 15 minutes before beginning to stream definitely seaward. It then streamed outward and downward across the sloping bench.

The foregoing observations show that there is a definite outward-moving bottom current in the shallow water over the reef flat and upper reef slope, at least at times of receding tide. Time did not permit repetition of the observations with an incoming tide, but I would expect the same pattern--the water that runs onshore at the surface because of the breaking waves must move offshore at the bottom. The fact of most importance is that this current is downward as well as outward, literally dragging the bottom, and at times of outflow between swells at the reef margin its force is memorable. Moreover, as this movement is perceptible even beyond the reef front at times of only moderately strong surf, it is probably considerable during storms. This is of importance in connection with the origin of reef front grooves and surge channels.

ORIGIN OF REEF-FRONT GROOVES AND SURGE CHANNELS

The fronts of most organic or limestone reefs that are exposed to the sea somewhere show a comb-tooth pattern of closely spaced grooves that are separated from one another by rocky buttresses. The parts of these grooves that transect the surf zone (and the coralline ridge if one is present) are called surge channels (Tracey et al, 1948, p. 867).

The origin of these groove-and-buttress systems is a vexing question, for they show features attributable to both biogenic construction and mechanical erosion. Ladd and others (1950, p. 413) have emphasized the importance of outgrowth of algal spurs to form the buttresses at Bikini atoll. They believe that although there probably "is mechanical abrasion during periods of exceptionally heavy weather...this does not seem adequate to explain the grooves as erosional figures." David and Sweet (1904, p. 81) explained them by a hypothesis of combined growth and erosion factors and Kuenen (1933, p. 80-81) believed that they were mainly constructional.

Newell et al (1951, p. 25), with reference to the Bahama Islands, inclined to the view that "the grooves are cut," and to judge from the fact that the grooves observed by them "are incised in oölitic country rock they evidently are erosional features." Before learning of Newell's views, studies of grooves and surge channels on Onotoa and previous observations of similar features on Guam, Saipan, and elsewhere had lead me to recognize erosion as important in the formation of the grooves. I have also seen, but not studied, grooves similar in plan to more conventional surge channels in the face of a basalt-floored bench just west of Haena point in northwestern Kauai, of the Hawaiian Islands.

In my opinion the grooves in many places are initially cut by outflowing undercurrents that carry tools of abrasion not available to the more spectacular inrushing surf. This produces the characteristic radial pattern of gravity flow. It is further suggested that most of this cutting followed falls of sea level, when reduction of bench surfaces provided maximum quantities of detritus for abrasion. Under proper light conditions air photographs of some shores (e.g., north Saipan) show several levels of offshore and even elevated grooves, not closely matching at their boundaries. These indicate groove-cutting at successive stands of sea level related to bench formation. Once a bench is reduced to equilibrium level, however, growth factors become relatively important. The abraded upper sides and crests of spurs then become veneered with growing coralline algae and corals, and the grooves may be masked over and generally closed or partly closed at the surface. This produces under-reef caverns and blowholes. Growth of algae and corals subsequent to groove cutting may be so extensive as to mask completely the evidences of abrasion, but the grooves and surge channels are found at so many places, and the radial pattern is so like the normal gravity pattern found on rilled rock beaches and elsewhere, that abrasion by outflowing gravity currents probably determined the basic pattern at many places where organic growth is the prevailing modern feature.

Many grooves and surge channels observed on Onotoa and elsewhere are undercut at their basal sides and floored with gravel, and many on the leeward coast of Saipan end in submarine potholes containing coarse gravel. The grooves are ordinarily most abundantly developed on windward reefs, but they have been observed in all quarters of the wind and at places are common on leeward reefs. Their degree of prominence is believed to be controlled by

strength of outflowing current, and thus surf, and by quantity of abrasive materials in transit. On the other hand, there are places where growth alone may produce the comb-tooth pattern. Both mechanical erosion and organic growth must be considered important in the origin of groove-and-buttress systems, the part played by each probably varying according to local conditions.

On Onotoa the grooves of the windward reef are almost limited to the surf zone and are thus synonymous with the surge channels, but traces of them run across the benched slope of the upper reef, masked by coral growth and debris. The front of the reef at the landward side of this bench is about 12 feet high and from the seaward side looks like the truncated spur-and-canyon topography of a steep-fronted and flat-topped mountain range or plateau. The surge channels range in length from about 50 to 80 and rarely as much as 120 feet. They are about 6 feet deep at midlength, and deepen gradually to about 8 feet at the reef front, with a downward dip of another 2 to 4 feet as they pass beyond the wave-breaking front of the reef. They range from 2 to 8 feet in width at the reef front and are undercut up to 1 foot on each side at their bases. Living algae and corals are abundant only at the crests and upper sides of intervening buttresses. The surge channels are floored with very coarse mostly slabby gravel. At the reef front above this gravel during a period of relatively strong surf (swell measured 6 feet high, combers averaged an estimated 8 feet), the only movement experienced was an up and down with the swell. Down in the lower part of the channels, however, the swimmer is carried back and forth with the surge for as much as 15 to 20 feet at a time. Under these conditions only small pieces of the gravel were observed to move, the maximum size observed in movement being a slab about 8 inches in diameter that rocked gently back and forth without being transported from its original position. Slabs this size and larger, although well rounded, are mostly

coated with a fairly luxurious felt of living green algae, and it is evident that their rounding occurs only at times of storm or very heavy surf, with plenty of time between for growth of algae. Whereas there is apparently enough movement of the boulders and smaller gravel and sand to prevent growth of coral and coralline algae on the floor and lower parts of the surge channels (except locally at their mouths), the grooves are probably not being significantly enlarged at the present time.

It is suggested that most of the groove cutting in the reef front at Onotoa occurred during beveling of the present reef flat after the recent 6-foot eustatic fall of sea level.

On Onotoa, evidence for Recent lowering of sea level of the order of 5 or 6 feet is found in remnants of an elevated Heliopora reef flat that occurs up to about $2\frac{1}{2}$ feet above the inner edge of the reef flat, both on the beach and in wells (e.g., profile 5, fig. 3). The inner edge of the reef flat, in turn, is estimated to be 2 to 3 feet above present mean low low tide. At present the upper limit of living Heliopora flats is about at low tide level. Similar occurrences of relatively elevated Heliopora flats are also found at Funafuti (Sollas, 1904, pp. 21-24; David and Sweet, pp. 67-68 and plates). Further evidence of a fall of sea level of about 6 feet at Onotoa is provided by elevated cobble stripes of a sort that I have observed only on reef flats. These cobble stripes rise about 2 or 3 feet above a surface of cobble gravel that is about 6 or 7 feet above the present reef flat at the northwest end of Onotoa and are separated from the lower-lying present reef flat by a gravel rampart.

As a Recent world-wide 6-foot fall of sea level may be amply documented, the evidence on Onotoa is only part of the broad picture. The higher stand from which the present sea has receded is provisionally attributed by Stearns (1941, p. 780) to the postglacial optimum temperature cycle of 5000 to 7000 years ago, when water previously and now tied up in the polar ice caps was in the ocean. Fall to present sea level probably took place in two steps, the first a 3- or 4-foot drop and the second 2 or 3. Evidence for the second drop consists of a bench about 2 or 3 feet above the present reef flat at Onotoa and elsewhere (see Kuenen, 1933, pp. 66-70; Dana, 1872, pp. 333-346). No attempt will be made here to summarize the large literature on the question of recent eustatic falls of sea level.

Atoll islands characteristically consist of unconsolidated debris resting on a solid foundation. This foundation must be broad enough and high enough so that this unconsolidated debris can accumulate beyond the reach of strong wave action and be preserved there. The foundation may consist of a reef that has grown to the surface of the sea, or which, having grown to the surface, is left somewhat above normal sea level by recession of the sea.

On a surface which is exposed between tides, lime-precipitating and sediment-binding green and blue-green algae flourish, and even coarse clastic materials are quickly and firmly bonded together by interstitial calcium carbonate. This is demonstrated by the cementation of blocks in the stone-ring fish traps on the outer reef flat and by firmly welded bars of boulder conglomerate at Aonteuma and at the northwestern extremity of the atoll. Upon such an intertidal surface, also, debris tossed by the waves has a good chance of remaining in position at a distance from the reef front that varies with the transporting power of storm waves.

The first step in the building of an atoll island, then, is the erection by storm waves of a ridge or rampart of coarse gravel on a living reef flat or wave-cut bench. Seaward additions may, of course, be made to such a rampart by subsequent storms. However, evidence that the structure is essentially stable along a given line and under prevailing strength of waves is found in the fact that the gravel rampart is a single ridge at most places.

Building of land on the lagoon side of this rampart is harder to understand. That much of the work is done by wind is evident from the prevalence of dune sands at many places, but from where does the sediment come? In the sands of Onotoan islands it is clear from the abundance of the reef-flat dwelling foraminifer Calcarina that much if not most of the sand is derived

from the reef. The tests of Calcarina and other Foraminifera that inhabit the algal mats of the reef flat apparently were washed across the reef and drifted around the ends of and along the lagoon side of the gravel rampart by local currents. The washing of water across the reef through breaks in the rampart is a sufficient explanation of the currents, but they may be locally emphasized or negated by other factors, such as wind. In the job of island building these currents will be aided by wind-borne sand from tide flats or from bars produced by the currents along the growing shore in the lee of the gravel rampart.

The island should continue to grow in width as long as there is a base for it to spread lagoonward on and a supply of sediment for building. The latter is provided by Foraminifera and clastic particles of $CaCO_3$. Eventuall if the process continues, and currents do not keep the lagoon swept free of sediment, the lagoon must fill up and a large land area develop, as at Chris mas Island, in the northern Line Islands. The height of an atoll island, insofar as it is not attributable to fall of sea level or to rampart buildin depends on the height to which wind can build dunes on the base provided and from material at hand. Most atoll islands are relatively narrow and low, seldom anywhere exceeding 12 to 18 feet above the reef flat. In my opinion this indicates that they are also relatively modern phenomena. Several au- thors have suggested that the building of atoll islands has been accelerated by and perhaps dates from the Recent 6-foot eustatic fall, and such an inter pretation would help to explain much of what is known of these islands, thei biotas, and human migration in the Pacific. This recession of sea level wou have resulted in an apparent elevation of near-surface reefs, providing exce lent bases for land construction of the type the atoll islands show.

The common presence of a lengthwise depression or depressions within atoll islands is explained by the outlined manner of growth. In the early stages of the process the currents from the ends of the islands would tend to swing a little away from the gravel rampart and build a longshore bar on the lagoon side. Subsequent additions are made mainly to the lagoon side of this longshore bar, and sediment is added to the depression areas only as it may blow in or wash over bar or gravel rampart. On Onotoa the inner depression is only locally present. However, the process that results in an inner depression is perhaps exemplified at both ends of the atoll islands by the arcs of land whose sandy extensions curve around tidal inlets (fig. 2). The general pattern of distribution on Onotoa of sand toward the lagoon and gravel toward the sea, and of islands mainly to windward, also is consistent with the patterns of other atolls and with the process suggested. Storms that either washed across or broke through the gravel ramparts or swept in gravel from the lagoon may be called upon to explain gravel deposits lagoonward of the rampart. Stages in island growth, according to the scheme outlined, seem to be illustrated by the longitudinally paired island strips of Marakei Atoll in the Gilberts (Agassiz, 1903, pls. 149-150) and by the filling since 1900 of lakes in the central depression of Putali Island on Addu Atoll in the Indian Ocean (Sewell, 1936a, p. 77). Sewell also shows (loc. cit.), by reference to pumice lines, that "the inner beach of the island has advanced toward the lagoon by some 10 yards" between about 1885 and 1934.

The gravel rampart itself is commonly capped and at places completely concealed by a veneer or thick cover of fine-grained younger dune sands, blown ashore from the reef-flat area so recently as to show no humus layer, or thinly to veneer a humus layer below. This sand contains few Foraminifera and

is thought to be mostly derived at times of low tide from the fine $CaCO_3$ particles that adhere to the drying surfaces of the green and blue-green algae of the inner reef flat. The probability that even extensive windward beach-zone dune belts cap gravel ramparts seems strong enough to warrant the showing of inferred ramparts beneath such dunes on the island profiles of figure 3.

If the islands of Onotoa were mainly built on a platform residual from the 6-foot stand of the sea, and if this stand of sea is properly correlated with the postglacial optimum, all of these land-building events have taken place in about the last 4,000 to 7,000 years.

Atoll islands appear to be eroded primarily at times of great storms by breaching of islands or by the complete removal of islands and other sediments on stretches of the reef flat. If at least the seaward portions of the unconsolidated atoll sediments rest on a bench surface at a higher level than the reef flat, as at Onotoa, destructive processes should be retarded. Remnants of beach rock on denuded reef flats and buried or outcropping beach rock within land areas provide the best basis for reconstructing stages in the building and erosion of atoll islands, once given a foundation.

SHIFTS OF SEA LEVEL AND THEIR EFFECTS ON MODERN REEFS

The reef flats of Onotoa on which islands are situated are truncated surfaces. Green algae thrive on the inner reef flats. A few corals and abundant red algae are found on their seaward portions. Evidence that this surface has been truncated is found in the elevated Heliopora flat that dips under the islands. This surface is continuous, at places observed carefully, with an old, truncated Heliopora flat that runs across the present reef and is merely veneered with algae and the sediments which they bind and cement to rock. Evidence of a former stand of the sea about 6 feet above present sea level is found in the elevated area of reef-flat cobble stripes at the northwest end of Onotoa, and also in the elevated and truncated surface of the old Heliopora reef.

At Arno Atoll, in the southeastern Marshall Islands, coral growth flourishes at least on many parts of the reef flat. Of this atoll Wells (1951, pp. 4-5) has stated that there is no evidence of fall of sea level, and the same is commonly reputed to be true of atoll islands. On the other hand, evidence of fallen sea level has been recorded at Bikini (Ladd et al, 1950, pl. 4, p. 413), Funafuti (David and Sweet, 1904, p. 67-68), and Horsburgh atolls (Sewell, 1936b, p. 121). Regardless of the fact that independent confirmation cannot everywhere be found, there is widespread and impressive evidence not only of a recent 6-foot eustatic fall of sea level, but of a very recent fall of roughly $1\frac{1}{2}$ to 3 feet and of one or more former sea levels in a range of 16 to 35 feet above the present one (Daly, 1920; Daly, 1926, pp. 174-179; Kuenen, 1933, p. 66-70; Stearns, 1941, p. 779-780; Stearns, 1945). The 16- to 35-foot zone is obscure, and its effects on modern reefs can only have involved shoaling preparatory to later events of

more significance to their present aspects. The 1½- to 3-foot fall seems best considered as a temporary stand in the lowering of the sea from the 6-foot level. There have also been local and perhaps eustatic positive movements of sea level, but positive eustatism for any given level is hard to demonstrate and relates only indirectly to the question here considered.

The evidence at hand suggests that the present superficial aspects of reefs are related to whether their surface was within 6 feet of sea level at the time of the 6-foot eustatic stand. If they lay below 6 feet, the drop in sea level would not have affected them markedly, and, if not sites of islands, they would presumably be flourishing organic reefs today. At such places no evidence of eustatic fall would be found except, in an indirect way, islands themselves, the construction of which would be facilitated by the shoaling of their potential foundations. If the surface of a reef were within 6 feet of sea level at the time of the 6-foot eustatic stand, it would be abraded and truncated with fall of the sea. It would be an area poor for growth of corals and crustose coralline algae, and veneered with clastic debris and soft algae or articulate corallines. Such reefs are found at Onotoa, Taraw, and Butaritari in the Gilbert Islands as well as in many other parts of the Pacific. In my opinion they are in themselves evidence of recent fall of sea level. Of course, it is to be expected that nontruncated reefs will be found in areas of truncation, for it is highly unlikely that all reefs of a given area or all parts of a given reef would have grown to uniformly shoal depths prior to the 6-foot fall.

A second feature of interest in connection with the Recent 6-foot fall of sea level is the already discussed development of grooves and surge channels in the present reef rim. It is here considered that such features at many or most places originally result from abrasion by gravity currents flowi

outward across the reef and equipped with abrasive tools provided by truncation of a relatively elevated reef flat. When such a reef flat is reduced to a stable level, or before, if conditions are favorable, growth of coralline algae and corals at the beveled reef margins is accelerated and eventually masks or even eradicates evidences of abrasion. The east end of Tarague Beach, at north Guam, is believed to exemplify an elevated bench in process of such reduction. For some unknown reason it, alone of all reef-flat areas seen on Guam, preserves numerous remnants of the older level between grooves that extend across the entire reef flat--as, of course, they should do until such time as lateral cutting processes reduce them to a general level.

A corollary of the contention that the 6-foot eustatic fall exerted a controlling influence on the superficial aspects of modern organic reefs is that one should be able to state, from the nature of its surface, whether or not any given reef area was within 6 feet of sea level at the time of the 6-foot eustatic stand. If it is sparse in living coral and veneered with green algae and clastic debris, and particularly if it is also a relatively smooth surface, it was probably truncated. If coral growth is vigorous and the surface irregular, it was probably not within 6 feet of the old sea level, or else it has grown up from a very severely beveled reef margin.

APPENDIX A--LIST OF REEF BUILDING CORALS AND HYDROZOANS

For the following preliminary identifications of corals and reef building hydrozoans from Onotoa I am indebted to Dr. J. W. Wells. The list given is composite for all localities and environments collected. Altogether it includes 26 genera and 50 to 60 species of corals and 2 genera and species of hydrozoans.

Scleractinia

Acropora humilis (Dana)

Acropora spp.

Astreopora sp.

Coscinarea columna (Dana)

Culicia

Cyphastrea micropthalma (Lamarck)

Echinophyllia aspera (Ellis and Solander)

Echinophyllia sp.

Echinopora lamellosa (Esper)

Favia stelligera (Dana)

Favia spp.

Favites sp.

Fungia concinna Verrill

Fungia scutaria Lamarck

Fungia valida Verrill--a new record

Goniastrea pectinata (Ehrenberg)

Goniastrea retiformis (Lamarck)

Halomitra philippinensis Studer

Herpolitha limax Esper

Hydnophora microconos (Lamarck)

Hydnophora rigida (Dana)

Leptastrea purpurea (Dana)

Lobophyllia sp.

Merulina sp.

Montipora caliculata (Dana)

Montipora foveolata (Lamarck)

Montipora verrucosa Lamarck

Montipora spp.

Pavona clavus (Dana)

Pavona varians Verrill

Pavona sp.

Platygyra rustica (Dana)

Platygyra sinensis (Edwards and Haime)

Plesiastrea versipora (Lamarck)

Plesiastrea sp.

Pocillopora caespitosa Dana

Pocillopora damicornis (Dana)

Pocillopora danae Verrill

Pocillopora elegans (Dana)

Pocillopora meandrina Dana

Pocillopora modumanensis Vaughan?

Pocillopora spp.

Porites andrewsi Vaughan

Porites lichen Dana

Porites lobata Dana

Porites lutea Edwards and Haime

Porites superfusa Gardiner

Porites spp.

Psammocora (Plesioseris) sp.

Seriatopora hystrix (Dana)

Tubastrea

Alcyonaria

Heliopora coerulea (Pallas)

Hydrozoa

Millepora tenera Boschma

Stylaster sanguineus Edwards and Haime

APPENDIX B--DESCRIPTION OF ECOLOGIC FIELD UNITS

Recognition of contiguous ecologic field units within a given general environment amounts to designating segments of a continuously variable sequence. Such units in large part express real central tendencies, but their boundaries are mostly indefinite, and to draw boundaries at all may be misleading. How to define the particular continuous variables in question and express them suitably on a map without recognizing suites of intergrading units is a problem yet to be satisfactorily solved. Pending such solution, or a reduction of categories on completion of laboratory studies and reevaluation of field data, the following descriptions may give the interested reader a more particular idea of the ecology of Onotoa.

Islands

Dune limesands

Younger dune sand. Mostly fine- to medium-grained, angular $CaCO_3$ sand. Humus layer incipient, thin, or absent.

Older dune sand. Similar to "younger dune sand," but with humus layer weakly to moderately well developed. In part rich in tests of foraminifer Calcarina.

Indurated dune sand. Indurated phosphatized (?) older dune sand.

Limesands other than known dune deposits

(Gravel intervals locally included in all types. Generally comprising most arable land and supporting thickest vegetation on Onotoa.)

Younger limesand. Fine- to coarse-grained sand, with humus layer thin or absent; locally includes gravel and wind-blown sand. According to local reports, the area of younger limesand and gravel on the point at Tabuarorae has been built since 1900.

Calcarina limesand. Sand of which 50% to 99% of the individual grains are tests of the foraminifer Calcarina. Generally with well-developed humus layer. Forms loose, well-drained soil with good capillary system. Favored for taro pits and breadfruit where ground water is sufficiently fresh.

Gravelly limesand. Sand with less than 50% Calcarina and with intermixed shelly gravel (abundant small Cardium, etc.) and small-pebble gravel.

Undifferentiated limesand. Fine- to coarse-grained sand with generally well-developed humus layer, with less than 50% Calcarina, and with little or no shelly gravel.

Limesilt grading to limesand. Mapped only in low, permanently damp areas. Generally wet and stiff. Humus layer poorly to moderately well developed. At places encrusted with caliche-like hardpan. Supports salt-tolerating shrub Pemphis (As well as poor coconuts, sparse Pandanus, etc.). Favored for retting pits because generally brackish water lies close to surface.

Limegravels

(Intervals of mostly angular sand locally included in all types)

Elevated flat-cobble stripes. Low ridges or stripes of cobbles oriented normal to beach line, similar to ridges that develop on modern gravel-veneered reef flats. No humus, few fines. Stripes are about 3 feet high, and bases of troughs between them are about 6 feet above present reef flat (hand level data). This is taken as evidence of a recent relative elevation of about 6 feet and correlated with the now well-documented Recent world-wide 2-meter eustatic fall of the sea.

Coarse coralliferous gravel. In part composed of large meandriform and astraeiform coral heads. Has little or no humus and few fines. Grades to "coralliferous pebble gravel."

Coralliferous pebble gravel. Fragments of branching Acropora conspicuous--also includes Heliopora and other corals, corraline algae, and mollusk shells and fragments. In coarser range grades to "coarse coralliferous gravel" and at many places includes areas or intervals of such gravel. In finer range grades to sands by increasing proportion of fines and reduction in size of gravel, and in such places approaches soil and vegetation characteristics of limesands.

Caliche

Caliche. Caliche-like limestone, not similar to beachrock. Found at one locality about 3 feet above reef flat level and behind sea-facing boulder rampart (north end of northern large island). Very thin crusts of caliche also occur at the surface of the enclosed Pemphis flats near this locality and in low places that are floored with wet limesilt.

Land bound areas of permanent brackish water

Brackish water ponds. Maximum depth 3 to 4 feet, blue-green algae abundant.

Blue-green algae flats. Areas of very fine $CaCO_3$ sediments rich in moderately to slightly brackish water cover nowhere exceeding 1-foot depth at normal tide level and in places barely enough to keep the ground wet. Covered with cauliflower-shaped nodules or mats of sediment-binding and lime-secreting blue-green algae.

Intertidal environments except reefs

Unconsolidated beach

Includes sand beach, gravel beach, sand and gravel beach, boulder beach, and outer beach.

Outer beach. Sand beach off lagoon side of southern main island that extends

beach proper beyond normal tide range and is exposed only at low low tides. Similar to "limesand flats" but narrower and sloping 3° to 5°.

Rocky beach
(Some units described here also occur inland and above normal tide range)

Concordant beachrock. Conformable with present beaches and certain tide flats. In large part little eroded, but commonly rilled and pitted with tide pools. Comprises limesandstone with dips 5° to 7° lagoonward on lagoon beaches and nearly horizontal on protected tide flat areas. On sea-facing beaches is limesandstone or coralliferous and algal conglomerate dipping 7° to 10° seaward.

Nonconcordant beachrock. Greater age than "concordant beachrock" suggested by occurrence at abnormally high levels, marked unconformity with present beach orientation, or unusually high degree of solution pitting in well indurated limesandstone. As mapped, probably in part includes "elevated reef-flat rock."

Bonded limesands. Weakly to strongly bonded limesands, commonly with a surface felt of sediment-binding (and lime-precipitating?) blue-green algae. At places consisting of successive layers separated by thin films of chlorophyll-rich sand that mark former exposed surfaces. Genera of algae provisionally identified from bonded limesands in the field by Dr. Edwin Moul are Chroococcus, Gomphospheria, Cleocapsa?, and other genera of the Chroococales, as well as Lyngbya and Scytonema. At places the bonded limesands show aberrant dips, some up to 30° landward, where they apparently have formed as depression fillings or perhaps slumped into cavities by collapse from beneath.

Elevated reef-flat rock. Old Heliopora-flat rock or rock consisting of fragments of coral and coralline algae in limesand matrix. The matrix may be partly or entirely a beachrock, but it lacks dip, is unbedded or very obscurely bedded, and is thus more suggestive of indurated reef-flat detritus.

Enclosed intertidal flats

Enclosed limesand, limesilt, or limemud tide flats. Fiddler crab (Uca) borings abundant, and odor of H_2S commonly strong in freshly exposed sediments. Permanently damp and saline, but flooded only at highest tide. "Mud" is used provisionally and in the sense of probable grain size only; it has not yet actually been determined that any of this material is a limemud.

Pemphis flats. Similar to "enclosed limesand, limesilt, or limemud flats," but with cover of the salt-tolerating shrub Pemphis. Found at shoreward margins of "enclosed flats." The shrub Pemphis, of course, also grows upon the land itself, at the edge of the beach or even inland in low places that are subject to periodic flooding or where the ground water is brackish.

Mangrove flats. Similar to "enclosed limesand, limesilt, or limemud flats," but with cover of the mangrove Rhizophora. Generally flooded at same stage of all tides, but mostly "dry" at lowest low tides. Sediments generally in the limemud to limesilt size range and high in H_2S.

Mainly intertidal flats adjacent to lagoon proper

(Units under this heading grade to lagoon, reef, and beach units)

Coral-algal rock flats. Dead coral-algal bottom veneered to a large extent with limesand and with local pockets where the sand is thick. Displays

occasional concentrations of the turtle grass Thalassia (and mostly unattached Microdictyon) and in areas of standing water, sparse living coral that consists mostly of stubbily branching Acropora, Pocillopora, and smallish, hassock-like Porites.

Coral-algal rock and sand flats with Zoanthus. Similar to "coral-algal rock flats" just described, but with sand veneer somewhat more conspicuous and supporting extensive growths of the colonial anemone Zoanthus as well as considerable numbers of varied green algae.

Limesand flats. Relatively "clean" sand-covered tide flats, with generally sparse megafauna of burrowing sipunculid worms, ghost crabs (Ocypode sp.), the snail Polynices, occasional cones and terebras, and, at places, the anemone Zoanthus and the common holothurian Holothuria atra Jager. Plants are scarce, but algae occur locally on erratic rocks, and Enteromorpha has been tentatively recognized. Zone extends beyond beach proper to the zero fathom line (mean low low tide) or slightly deeper.

Sand and gravel flats. Tide flats of calcareous sand and gravel with green algae resembling Cladophora and Cladophoropsis, Dictyosphaeria, and Valoniopsis abundant in portions that remain wet at normal low tide. A few living corals are present locally.

Sand and gravel flats with coral. Similar to and grading to "sand and gravel flats" just described, but with scattered living coral, chiefly hassock-like Porites. Invariably wet when seen, and presumably water-covered except at lowest low tides.

Cobble gravel flats. Cobble-veneered areas mostly lagoonward from reef flats, including occasional boulder or pebble fractions. Components mostly angular. Unit also includes indurated cobble conglomerate flats, adjacent to or continuous with reef flats (as adjacent to Aonteuma and at north end of reef flat beyond this islet).

Pebble gravel flats. Areas veneered mainly with pebble gravels, but with some cobbles. Individual coarse fragments primarily angular.

Beachrock ribbed tide flats. Low ridges of old beachrock interspersed with dirty limesand flats, incipient beachrock patches, and circular patches of Thalassia (and Microdictyon). The common sea cucumber Holothuria atra Jager very abundant locally in pools and permanently wet depressions.

Bars and spits

(Continuously exposed or inundated only at highest high tides)

Includes sand bars and spits, pebble gravel bars and spits, boulder gravel bars, and bars of sand and gravel.

Outer reef

Grooved reef slopes. Upper slope of either leeward or windward reef front marked with conspicuous grooves normal to reef front and separated by buttresses veneered with living coral.

Papillated reef slopes. Upper slope of leeward reef front papillated with scattered, but more or less linearly arranged, patch reefs of living coral and coralline algae.

Benched reef slope. Upper slope of windward reef front, comprising a bench that slopes about 15° seaward from a depth of about 2 fathoms to the upper part of a 30° to 40° undersea slope at about 9 or 10 fathoms. Bench generally veneered with a mat of living and dead coral, the predominant types being stoutly branched Pocillopora elegans (Dana).

Reef front. Coralline ridge and surge channels prominent on windward side, but ridge is weak or absent on leeward side. The coralline ridge is low, purplish-red in color, and thickly crowded with masses and crusts of coralline algae such as Porolithon and Gcniolithon. It runs along the

surf edge of the reef, is exposed at low tide, and is intersected by numerous channels through which surges the white water of the breaking surf. Presumably it was casual view of this reef front that led Setchell (1928, p. 1840) to state "the atoll of Onotoa...was composed, so far as visible, entirely of nullipore...largely if not entirely...Porolithon craspedium (Foslie) Foslie."

Red alga zone of windward reef flat. A permanently wet area of red algal growth landward from reef front. The outer part or subzone, an area of permanent standing water and locus of tidal fish traps, is called the back ridge trough. Here are scattered cabbage-shaped and branching masses and crusts of coralline algae such as Porolithon and Goniolithon and scattered large living heads of astraeiform and meandriform corals, as well as stubbily branching Acropora and Pocillopora. The green algae Caulerpa and Halimeda are found locally and sparsely in the back ridge trough. The inner part, or Jania subzone, of the red alga zone slopes up and grades to the green alga zone of the inner reef flat, their point of juncture being approximately defined by the inner edge of the fish traps. Biota of the Jania subzone dominated by articulate coralline Jania, with living Foraminifera of the genera Calcarina and Marginopora locally abundant. At places Jania subzone shows scattered, rolled coral boulders up to 16 inches in diameter, these boulders probably being broken loose within the back ridge trough.

Green alga zone of windward reef flat. Inner reef flat characteristically matted with green algae. Commonly divisible into outer, middle, and inner subzones. In the outer subzone the red alga Jania is an abundant holdover from the red alga zone, but green algae predominate. The intermediate subzone is one of flourishing green algae, and the inner

subzone is one wherein the green algae are whitened by encrusting bonded sediments or at places absent from the bare dead coral-algal rock below. At a distance these subzones seem sharply defined because of color differences, but they actually intergrade over rather wide intervals. Characteristic genera of algae throughout the green alga zone include Cladophora or Cladophoropsis, Valoniopsis, and Dictyosphaeria. At many places this zone is strewn with scattered, rolled meandriform and astraeiform coral heads up to 16 inches in diameter, these boulders probably being derived from the back ridge trough of the red alga zone.

Leeward reef flats. Lagoonward portion generally dominated by green algae; seaward portion characterized by abundance of articulate coralline Jania, crustose corallines, and scattered sturdily branched Acropora and Pocillopora.

Gravel and sand veneered reef-flat areas. Dead or decadent reef flat veneered with angular gravel of pebbles, cobbles, or boulders, and with a conspicuous fraction of sand. Living corals few.

Cobble and boulder veneered reef-flat areas. Dead or decadent reef flat veneered with cobbles and boulders. Sand inconspicuous.

Flat-boulder veneered reef-flat area. Chaotic coralliferous flat-boulder gravel on windward reef flat.

Gravel veneer on dead reef-breccia. Rough, angular, coralliferous cobble-pebble gravel with some boulders. Veneers surface of coral debris breccia that presumably represents old reef flat. At places old reef-breccia is bare, with no veneering gravel. Mostly covered only at high tide. Developed primarily between the two main islands.

Calcarina-Marginopora reef-flat areas. Protected reef-flat areas matted with living Foraminifera of the genera Calcarina and Marginopora, and with green algae, the Foraminifera commonly entangled in the algae. Scattered boulders and cobbles are common locally. A few specimens of the common black sea cucumber Holothuria atra Jager are found in permanently wet pockets.

Heliopora reef zone. Living Heliopora in essentially continuous and generally thickly arborescent reef growth, with Acropora and Porites secondary and other coral types minor.

Porites reef zone. Living reef area dominated by large flat-topped heads of Porites. Irregular coral growth on bottom having depths of several feet at low tide.

Acropora-Pocillopora reef zone. Living reef area of varied coral types dominated by varieties of Acropora and Pocillopora; corals thin out from reef flat toward lagoon or tide flats with increase in area of limesand bottom.

Varied reef zone. Reef area of abundant to scattered living coral growth of varied types on bottom of dead coral-algal rock that is at places extensively veneered with coral-algal gravel and limesand. Dominant living coral types are Acropora, Porites, Orbicella, and meandriform genera. Heads of coralline algae and pavement-type corallines locally abundant. Depths less than 1 fathom at low tide.

Heliopora flats. Living Heliopora scattered over and rising 1 to 2 feet above limesand bottom. Upper tips of Heliopora barely exposed at low tide. Minor gravel patches occur locally. The sea cucumber Holothuria atra Jager is common. Echinoids recorded include a large poisonous Diadema and the harmless Tripneustes cf. T. gratilla.

Decadent Heliopora flats. Includes scraggly truncated Heliopora, a few other species of coral, and green algae, interspersed on surface of limesand and gravel.

Dead Heliopora flats. Elevated, truncated, dead Heliopora reef flats. Essentially the same as the foregoing, but inundated only at high tide and thus with no living Heliopora.

Heliopora-Porites reef zone. Living reef area, mainly Heliopora, in large flat-topped heads crusted with Porites and crustose corallines.

Sandy reef zone. Mostly clean limesand with occasional living and dead coral at lagoonward margins of extensive leeward reef areas.

Intertidal to lagoonal environments

Thalassia flats and shoals. Dirty limesand with clusters or continuous mats of the turtle grass Thalassia. Commonly also with much of the green alga Microdictyon, the latter mostly unattached. The sea cucumber Holothuria atra Jager is locally very abundant.

Rocky flats and shoals. Bottom mostly of dead coral-algal rock patchily veneered with gravel and sand. Scattered but fair representation of living coral dominated by stubbily branching Acropora and Pocillopora and locally by hassock-like Porites. Circular patches of the marine grass Thalassia and the green alga Microdictyon occur locally at the beachward margin in the inner lagoon, and the brown alga Turbinaria is abundant at places. Holothuria atra is locally abundant.

Coralliferous rocky shoal bottom. Bottom similar to that of "rocky flats and shoals," but with fairly abundant living coral patches wherein stubbily branching Acropora and Pocillopora are dominant.

Enclosed inlet. Area walled off as pair of fish ponds. Supports thick growth of turtle grass Thalassia and many fish, including small sharks and an unknown fish that is much feared by the natives (apparently not a barracuda, to judge from the description, but was not seen by our field party). This area was not explored or sounded, but it is reported by the native, Kane, to be generally under 4 feet and nowhere more than 9 feet deep at low tide.

Environments of the lagoon and leeward shelf

The following units comprise a continuously variable sequence with more than usually indefinite boundaries:

Limesand bottom. Mostly clean limesand bottom at depths greater than 2 fathoms, living coral present locally.

Conspicuous lagoon patch reefs. Patch reefs of varied coral types and subordinate coralline algae, over 200 feet in diameter. Reef symbol on figure 2 used to indicate parts that are awash or nearly awash at low tide.

Limesand with scattered patch reefs. Mostly clean limesand floor, above which rise small scattered coral-algal patch reefs and pinnacles. Purely arbitrary and grades imperceptibly to limesand and patch reefs.

Limesand and patch reefs. Small patch reefs of varied coral types and subordinate coralline algae abundant but areally exceeded by limesand floor. Grades to "varied patch reefs and limesand," "Heliopora patch reefs and limesand," and "limesand with scattered patch reefs."

Varied patch reefs and limesand. Small patch reefs of varied coral types and subordinate coralline algae very abundant and only narrowly separated by areas of limesand floor.

Algal patch reefs and limesand. Abundant patch reefs of massive coralline algae and varied coral types presumably rising above limesand floor (bottom between reefs not observed or sampled).

Heliopora patch reefs and limesand. Abundant patch reefs consisting mainly of Heliopora in tree- and candelabra-like growths that produce a forest-like underwater scenery. In part the Heliopora patches are extensively masked by overgrowth of other coral types, and locally the patch reefs are of varied coral types. For the most part, intervening limesand bottom only narrowly separates individual patch reefs.

Varied bottom with scattered larger patch reefs. Subcircular patch reefs 100 to 300 feet in diameter scattered on bottom of limesand and limesilt with irregular low patches and small patch reefs of living coral and locally with abundant Halimeda. Depths between patch reefs mostly more than 3 fathoms, ranging to more than 7 fathoms locally. At shallow margin are several ridge-like patch reefs up to half a mile long.

Coral plantations. Coral and subordinate coralline algae essentially continuous or intimately intermingled with areas of dead coral on irregular bottom. Acropora the dominant genus in areas observed.

Limesand patches in coral plantations. Extensive areas of limesand and minor patches of coral within coral plantations.

REFERENCES

Agassiz, Alexander, 1903, The coral reefs of the tropical Pacific, Mus. Comp. Zool. Mem., vol. 28, 410 pp.

British Colonial Office, 1950, Report on the Gilbert and Ellice Islands Colony for the year 1949, B. C. O., London, 52 pp.

Carey, L. R., 1918, The Gorgonaceae as a factor in the formation of coral reefs: Carnegie Inst., Dept. Marine Biol., vol. 9, pp. 341-362, pls. 100-105.

Carey, L. R., 1931, Studies on the coral reefs of Tutuila, American Samoa, with special reference to the Alcyonaria: Carnegie Inst., Papers from Tortugas Lab., vol. 27, pp. 53-98, figs. 1-14, pls. 1-7.

Couthouy, J. P., 1844, Remarks upon coral formations in the Pacific; with suggestions as to the causes of their absence in the same parallels of latitude on the coast of South America: Boston Soc. Nat. History Journ., vol. 4, pp. 66-105, 137-162.

Daly, R. A., 1920, A general sinking of sea-level in recent time: Nat. Acad. Sci. Proc., vol. 6, no. 5, pp. 246-250.

_____, 1926, Our mobile earth, Chas. Scribner's Sons, N. Y., 342 pp.

Dana, J. D., 1872, Corals and coral islands, Sampson Low & Co., London, 398 pp.

David, T. W. E., and Sweet, G., 1904, The geology of Funafuti: Royal Soc. London, Rept. of Coral Reef Comm., The Atoll of Funafuti, sec. 5, pp. 61-124, pls. B-E in text, pls. 1-19 in separate portfolio.

Emery, K. O., 1946, Marine solution basins: Jour. Geology, vol. 54, no. 4, pp. 209-228, figs. 1-15.

Finckh, A. E., 1904, Biology of the reef-forming organisms at Funafuti Atoll: Royal Soc. London, Rept. of Coral Reef Comm., The atoll of Funafuti, sec. 6, pp. 125-150, fig. 19.

Freeman, O. W., et al., 1951, Geography of the Pacific, John Wiley & Sons, Inc., N.Y.; Chapman & Hall, Ltd., London, 573 pp.

Kuenen, P. H., 1933, Geology of coral reefs: The Snellius Exped. (Eastern Neth. E. Ind. 1929-30), vol. 5 (Geol. Results), pt. 2, pp. 1-125, figs. 1-106, pls, 1-11, Kemink En Zoon, N. V. Utrecht.

Ladd, H. S., et al., 1950, Organic growth and sedimentation on an atoll: Jour. Geology, vol. 58, no. 4, pp. 410-425, figs. 1-2, pls. 1-7.

Newell, N. D., et al., 1951, Shoal-water geology and environments, eastern Andros Island, Bahamas: Am. Mus. Nat. History Bull., vol. 97, art. 1, pp. 1-29, figs. 1-5, pls. 1-8.

Pacific Sci. Board, 1951, Handbook for atoll research: mimeographed, numerous small units by various authors, Nat. Res. Council, Washington, D. C.

Safford, W. E., 1905, The useful plants of the island of Guam: U. S. Nat. Mus., Contrib. from U. S. Nat. Herbarium, vol. 9, 416 pp.

Setchell, W. A., 1928, A botanical view of coral reefs, especially of those of the Indo-Pacific region: Third Pan-Pacific Sci. Congress, vol. 2, pp. 1837-1843.

Sewell, R. B. S., 1936a, An account of Addu Atoll: British Mus. (Nat. Hist.), The John Murray Exped. 1933-34, Sci. Repts., vol. 1, no. 3, pp. 63-93, fig. 1, pls. 1-8.

Sewell, R. B. S., 1936b, An account of Horsburgh or Goifurfehendu Atoll: British Mus. (Nat. Hist.), The John Murray Exped. 1933-34, Sci. Repts., Vol. 1, no. 55, pp. 109-125, fig. 1, pls. 1-6.

Sollas, W. J., et al., 1904, The Atoll of Funafuti: Royal Soc. London, Rept. of the Coral Reef Committee, Harrison & Sons, London, 428 pp., 19 pls. in separate portfolio.

Stearns, H. T., 1941, Shore benches on North Pacific islands: Geol. Soc. America Bull., vol. 52, no. 6, pp. 773-780, figs. 1-2, pls. 1-3.

_____, 1945, Eustatic shore lines in the Pacific: Geol. Soc. America Bull., vol. 56, pp. 1071-1078.

Tracey, J. I., Ladd, H. S., and Hoffmeister, J. E., 1948, Reefs of Bikini, Marshall Islands: Geol. Soc. America Bull., vol. 59, pp. 861-878, figs. 1-8, pls. 1-11.

U. S. Coast and Geodetic Survey, 1951, Tide tables, central and western Pacific Ocean and Indian Ocean: U. S. Dept. Commerce, Coast and Geodetic Survey, Washington, D. C., 343 pp.

U. S. Hydrographic Office, 1940, Sailing directions for the Pacific Islands, Vol. II: U. S. Navy Dept., Hydrographic Office Pub. No. 166 (Onotoa, p. 380), 522 pp.

U. S. Hydrographic Office, 1950, Supplement to Hydrographic Office Pub. No. 166, U. S. Navy Dept., Hydrographic Office Pub. No. 166, U. S. Navy Dept., Hydrographic Office Pub. No. 166-S, 85 pp.

Wells, J. W., 1951, The coral reefs of Arno Atoll, Marshall Islands, Nat. Res. Council, Pac. Sci. Bd., Atoll Res. Bull. No. 9, 14 pp., 16 figs.

Wentworth, C. K., 1947, Factors in the behavior of ground water in a Ghyben-Herzberg system: Pacific Sci., vol. 1, no. 3, pp. 172-184, figs. 1-4.

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Part I

by A. H. Banner

Part II

by John E. Randall

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SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

National Research Council

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Thanks are also due to Dr. Preston E. Cloud, Jr., the leader of the expedition, for the use of the map he made of the island, and to R. Tucker Abbott of the U. S. National Museum for the identification of some of the molluscs.

PREFACE

The marine biological work on Onotoa is divisible into five portions:

1. The investigation of shallow water ecological associations, reported herein:
   A. The ecology of the windward reef.
   B. The ecology of the lagoon reefs and shores.
2. The investigation of the deeper water ecological associations, to be reported by Dr. Preston E. Cloud, Jr.
3. The investigation of the marine algae, to be reported by Dr. Edwin Moul.
4. The investigation of the ichthyofauna, reported by Mr. John Randall and appended to this report.
5. The native use of the marine invertebrates for food, reported herein.

My portion of the study, the marine invertebrates, was severely limited by an attack of blood poisoning and a subsequent attack of influenza that resulted from attempting to do field work when not fully recovered from the first illness; as a result of these two illnesses, over five of the ten weeks spent on Onotoa were lost and the investigations made were neither as thorough nor as extensive as planned.

The following reports are preliminary, and should be taken to show merely the extent of the work done. The identifications are field identifications and must be confirmed by experts, with the exception of some of the molluscs which have already been identified by R. Tucker Abbott of the U. S. National Museum; and no conclusions are incorporated in the reports. When these reports are published the deficiencies will be corrected.

PART I

I

WINDWARD REEF TRANSECT

The windward reef on Onotoa is found along the northern, eastern and southern shores of the atoll, presenting an almost unbroken barricade against the force of the prevailing waves. It varies in width from three or four hundred feet to over a quarter of a mile and is more extensively developed around the southern island than around the northern. As it is of quite uniform height, structure and biotic zones, a single transect across its surface was deemed to be indicative of the general ecology of the reef.

Conditions of the Reef

The inshore border of the reef is composed either of consolidated and eroded coral rock or moderately fine sand with the upper edge extending to the maximum height of the storm waves and the lower edge varying but usually about the 2.0 to 2.5 foot tide level. Beyond this steep shoreward area the reef flat extends to a uniform area of slight slope, with frequent small to large shallow pools of water left at low tide. The reef flat in the transect studied was 650 feet broad. Seaward of the reef flat is a depression, the back-ridge trough, between 50 and 100 feet wide and ranging in depth from about the + 0.2 to the - 1.5 foot tidal level. The final edge of the reef is the coralline ridge (or Lithothamnion ridge by previous workers), a rampart between 1.0 and 2.0 feet above the zero tide and 50 - 100 feet broad. Its shoreward edge presents an almost continuous front of reddish coralline algae, but on its seaward side soon develop deep fissures or surge channels at right angles to the shore that reach six or more feet below the surface of the reef and that are of varying width, widening as they reach seaward. The seaward edge of the coralline ridge thus separates into a series of

separate and depressed fingers that finally slope rapidly down to the growing reef surface below. The outermost reef or the reef shelf is relatively narrow, about three hundred feet wide, and slopes rather rapidly from about ten feet deep on the shoreward side to over thirty or thirty five feet deep on the seaward side; it consists of living coral growing in irregular mounds with areas between the heads strewn with dead coral fragments. Beyond this reef shelf the bottom drops suddenly away, at a slope of perhaps more than 45° and soon disappears in the turbid waters; this last zone was not explored at all.

The windward reef facing the trade winds sustains the almost continuous beating of the waves. At low tide the waves are broken against the coralline ridge and only slight waves are felt in the backridge trough. However, when the tide is high, only a portion of the strong waves is expended against the coralline ridge and the adjacent trough and moderate sized waves sweep across the reef flat, carrying enough energy to move coral rocks a foot or two in diameter.

The reef flat from the coralline ridge back is the evident result of the consolidation of a living coral reef, chiefly of Heliopora, by coralline algae; in almost all areas the old Heliopora is completely dead and covered with the algae to make an almost table-like top. This top, however, is pitted with small to large depressions, and in many areas perforated by burrows leading down among the old coral fronds.

Animals living upon the flat are subjected to many biological vicissitudes in addition to the action of waves. In the inshore area especially the reef flat is exposed to the air for several hours at a time at the lower low waters, and those animals that cannot migrate to the shallow pools must be able to withstand this period of dessication. Those animals in the pools, as well as those exposed to the air must also be able to withstand great changes in

salinity of their environment, for the high tide has the normal ocean salinity, while the low tide may expose them to torrential rains which would lower the salinity of the topmost layers at least to almost zero. However, because of the difference in specific gravity and the absence of agitation in these small bodies of water it is likely that the bottoms of the pools and the burrows in the rock especially maintain their normal salinity.

Probably the most pronounced physical change the animals are subjected to is the change in temperature for the dark reef surface on low tides is exposed for long periods to the tropical sun. At these times the water in the inshore pools become hot to the touch (studies on temperature made by Strasburg will be reported by Cloud): yet with the flooding tide the temperature will drop perhaps 15° in a few minutes.

Previous studies have shown that the oxygen content of the water over the reef at high tide and in the pools at low tide is always near if not above its saturation value. But as the temperature rises this saturation value, in grams of oxygen per liter of sea water, decreases rapidly, so the reef inhabitants must be able to adjust to less than normal oxygen.

Two biological conditions of the reef flat should be mentioned as influencing its ecology. In the first place the reef surface not in the small tide pools is covered in most areas by a dense algal mat that affords both food and protection for the inhabitants; this was particularly true in the middle and outer portions of the reef flat. Secondly, while few larger predators and scavengers like larger fish, lobster and crabs were found while the survey was conducted at low tide, they moved onto the reef at high tide.

Methods and Limitations of the Study:

The objects of the investigation were to find the transition of dominant forms over the reef surface, and, if possible, to designate sharply delimited

zones on the reef through a quantitative study.

On the main reef flat the study was conducted by laying out a series of continuous stations, twenty feet wide and fifty feet long, and within them areas extending the length of the station one or two feet wide. Within the smaller area all animals were collected and counted; the larger area was then inspected for larger but less common animals like the larger snails, sea cucumbers, etc. Then areas in the same tidal zone adjacent to the studied area were superficially examined to see if the zone selected was typical; it was found so in all cases.

In the inshore beach area, in the backridge trough, and over the offshore shelf no quantitative study was attempted because of difficulty in obtaining either enough animals in a typical area or because of the difficulty in laying out an area for study and collecting it (as in twenty to thirty feet of water). Because of poor tides and poor weather conditions when it was possible for me to do field work, almost no study was made on the coralline ridge at all.

The limitations of the study are:

1. The study is limited to macroscopic invertebrates; no microscopic forms of life nor any fish are considered. Mr. Randall did a parallel study on fish and will report it separately.

2. Concerned as it is with the dominant animals, this study omits the more rare animals.

3. All identifications of animals are but field identifications, and will be corrected upon the identification by experts.

4. The study is limited by necessity to the more superficially occurring animals; it was impossible to explore the tubes reaching down from the consolidated surface of the reef.

5. No statistical checks have been applied to the quantitative results, and they should be accepted merely as rough indications rather than accurate statistics; in other words, a similar section two hundred feet away might give different figures, but would show the same trend.

Transect

Area A-0; Shoreward beach.

The well-demarked beach extends from about 2.5 feet to about 8-10 feet above the zero tide zone. It is divisible into two different habitats, the sand beach composed of loose and shifting sand, and the rock beach consisting of consolidated coral and beach rock, eroded and with some small tidal pools.

The sand beach is the habitat only for Ocypode ceratophthalma, the "ghost crab" that lives in deep burrows by day; also at night terrestrial hermit crabs migrate down to the upper zones of the beach.

The rock beach is inhabited by Grapsus grapsus in fair numbers, some identified hermit crabs, and large numbers of *Nerita plicata (species marked * indicates the identification has been confirmed by R. Tucker Abbott.)

Areas A-1 to A-14.

These stations covered the reef-flat and present roughly the same type of substrate. The surface is relatively smooth, being built up by the consolidation of the individual heads and fronds of coral by coralline algae. Its surface is pitted with small shallow depressions in which water stands at low tide; these are usually less than a square foot in area and not over about three inches deep. The exposed surface of the coral and in some areas the tidal pools, are usually covered with a more or less dense growth of algae (to be reported by Dr. Moul). The exceptions to these generalizations are in the back-ridge trough (areas A-13 and A-14) where the surface is below the level of the lowest tides. Areas A-7 and A-8 and A-9 were at least in part covered by a single extensive tide pool; in these areas a few living pieces of Heliopora were still growing uncovered by coralline algae.

TRANSECT, WINDWARD REEF FLAT

Stations A-1 to A-14

In the tabulations below those animals not quantitatively estimated and those animals that are rare, scattered or very irregular in their occurrence (as would be those found only in the occasional loose coral boulders) are indicated by P for present.

Station	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Distance from beach	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700
Height above 0.0 tide zone	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	1.0	0.8	0.6	0.4	+0.4 to -0.2	-0.2 to -1.4
Approximate percentage covered by tidal pools.	70%	30%	30%	50%	30%	30%	80%	100%	90%	70%	80%	70%	20%	100%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RIFERA														
Black Sponge	-	-	-	-	1	80	20	40	60	-	1	120	-	-
Purple Sponge	6	11	3	1	40	100	40	-	-	-	-	-	-	P
Yellow Sponge	-	-	-	-	-	-	-	-	-	-	-	-	-	P
ELENTERATA														
Heliopora sp.	-	-	-	-	-	-	-	2P	5P	-	-	-	-	-
Zooanthids	-	P	-	-	-	-	-	-	-	-	-	-	-	-
Sea Anemone	60P	-	-	-	-	-	-	-	-	-	-	-	-	-
Porites lobata	-	1	-	-	-	-	-	-	20	100	20	240	4P	-
Porites (papilliform)	-	-	-	-	-	-	-	-	-	-	-	-	-	P
Pocillopora meandrina	-	-	-	-	-	-	-	-	-	-	-	-	-	3
Acropora sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	10
Orbicella	-	-	-	-	-	-	-	-	-	-	-	-	P	P
Goniastraa	-	-	-	-	-	-	-	-	-	1	-	20	-	-
Platygyra rustica	-	-	-	-	-	-	-	-	-	-	-	-	-	P
TYHELMINTHES														
Polyclad	-	-	1	-	-	-	-	-	-	P	P	-	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
NEMERTEA														
Nemertine	-	-	-	-	-	-	-	-	-	-	-	-	-	P
ANNELIDA														
Eurythroe sp.	-	P	-	-	-	-	-	-	-	P	40P	1P	-	-
Other Errantia	-	P	P	11P	P	P	-	-	-	P	-	120P	-	P
Tubeworms with foraminiferal tubes	-	P	P	-	-	80P	4P	P	P	-	-	-	-	-
Sipunculus sp.	-	P	P	P	P	P	20P	-	-	P	-	-	-	-
CRUSTACEA														
Stomatopoda (Pseudosquilla ciliata)(?)	-	P	-	1P	1P	-	-	-	-	P	P	80P	-	-
Crangon sp.	-	P	17P	70P	120P	-	20P	20P	P	P	40P	140P	P	1P
Synalpheus sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	1P
Shrimps, other	-	-	-	-	3P	-	-	40P	-	-	-	-	-	P
Callianassa sp.	-	-	-	1P	-	-	-	-	-	-	-	-	-	-
Paribaccus sp.	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Hermit crabs	800	87	689	1500	3400	3900	1720	111	60	-	-	-	-	-
Dromia sp.	-	-	-	-	P	-	-	-	-	-	-	-	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
halmita edwardsii	-	-	-	3P	40P	-	-	-	-	-	-	-	-	-
rapezia	-	-	-	-	-	-	-	-	-	-	-	-	-	19P
rapsoid crabs	-	-	-	-	-	-	80P	-	-	-	-	-	-	-
ybia tessa-lata	-	-	-	-	-	-	-	-	-	-	-	-	-	1P
rabs, other	20P	P	P	P	P	P	P	120P	P	P	20P	-	-	P
STROPODA														
atelloida sp.	-	-	-	20	-	-	-	-	-	-	-	-	-	-
atella stellaefor-nis	-	-	1	-	-	-	-	-	-	-	-	-	-	-
erita blicata	50,000	6000	4	-	-	-	-	-	-	-	-	-	-	-
erithium concisum	1100	200	28	20	-	-	-	-	-	-	-	-	-	-
erithium obeliscus	-	-	-	20	20	-	-	20	-	1	-	-	-	-
erithium columna	-	9000	1420	1000	20	20	-	20	-	-	-	-	-	-
utica sp.	-	3	3	20	0	-	-	-	-	-	-	-	-	-
onetaria noneta	6	18	30	50	140	160	40	180	100	80	5	-	-	-
nularia uricina	-	10	4	4	-	-	60	20	40	40	-	-	-	-
mathium chlorostomum	-	-	1	1	20	-	-	-	-	-	4	-	-	-
rsa bufonia	-	-	-	-	-	-	-	-	-	40	4	60	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cyroscala perplexa	-	-	-	20	-	-	-	-	-	-	-	-	-	-
*Thais hippocastanum	4	7	16	20	3	2	-	-	-	-	-	-	-	-
Vasum ceramicum	-	-	-	-	-	-	-	-	-	-	20	2	2P	-
*Mitra litterata	250	85	49	500	160	40	50	20	20	40	80	100	-	2P
*Mitra virgata	5	-	-	-	-	-	80	-	-	40	-	-	-	-
*Engina mendicaraia	150	8	21	70	40	4	-	-	-	-	-	-	-	-
*Drupa grossularia	-	2	1	-	-	-	-	-	-	-	-	20	-	-
Drupa ricina	-	-	1	-	-	-	-	-	-	-	-	-	-	-
*Morula granulata	52	30	6	6	1	-	-	-	-	-	20	40	-	-
*Morula fiscella	150	-	-	20	-	-	-	-	-	-	-	-	-	-
*Conus hebraeus & C. spondylus	22	81	100	500	140	60	60	120	-	2	1	-	-	-
*Conus miliaris	-	2	8	70	1	-	1	20	20	-	1	-	-	-
Conus flavidus	-	-	-	-	-	20	-	20	-	-	1	-	1P	-
Conus sp.	1	-	-	-	-	-	-	60	-	-	-	-	-	-
Cythara sp.	-	-	-	200	20	280	-	-	-	-	-	-	-	-
*Torinia varigata	1	1	2	20	20	20	-	-	-	-	-	-	-	-
Vermitidae	2	-	-	-	-	-	-	-	-	-	-	-	-	-
Nudibranch	-	-	1	-	1	-	-	-	-	P	-	-	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
LECYPODA														
arbatia tenella	1	-	5	P	20	40	360	390	1400	720	840	260	1P	-
olsella auriculata	-	-	-	40	-	-	-	-	-	-	-	-	-	-
sognomon perna	3	2	3	-	20	40	-	-	20	60	-	-	-	-
afrarium pectinata	-	-	2	-	-	-	-	-	-	-	-	-	-	-
HINODERMATA														
ripneustes pratilla	-	-	-	-	-	-	-	-	-	-	1	-	-	-
chinometra mathaei	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Cidema baucispinus	-	-	-	-	-	-	-	P	-	-	-	-	-	-
Istichopis sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	P
Ophiocoma brevipes	-	-	-	-	-	-	-	-	-	-	1	-	-	P
Other brittle stars	125P	2	8	-	1P	-	2P	-	-	-	-	120P	P	-
Holothuria atra	-	P	1	1	-	-	-	1	-	1	1	-	-	-
Stinopyga mauritana	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Other Holo-thurians	-	-	-	-	-	-	-	-	-	20	-	-	-	-
CHORDATA														
Polychodera sp.	1	P	P	-	20P	-	-	-	-	-	-	-	-	-

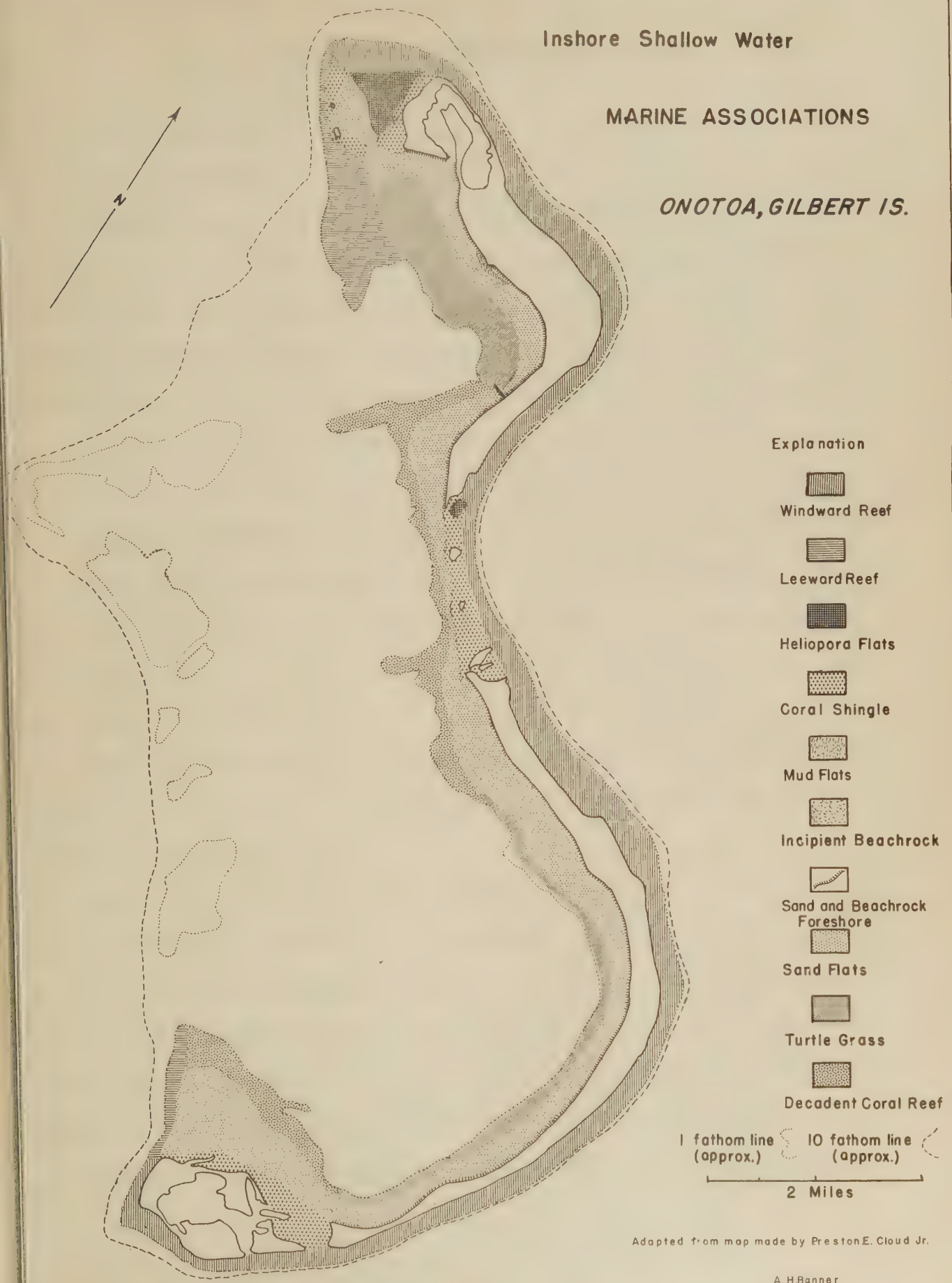
Coralline ridge.

The topographical features of this ridge are described above. Unfortunately tides and waves did not permit an examination, neither quantitative nor qualitative, of the fauna of this zone. The relatively smooth surface of the coralline algae did not offer any protection for animal life; the shifting rocks at the bottom of the surge channels offered less. However, reaching into the mass of the coralline algae were numerous openings, and within the heads were chambers in which many animals lived. In this habitat were found such animals as Echinometra mathei, Heterocentrosus sp., and several species of xanthid crabs.

Reef Shelf.

This area, lying beyond the outer edge of the coralline ridge, was estimated to be about 300 feet wide, from 8-10 feet deep at the coralline ridge to about 30 feet deep where the bottom begins to drop away abruptly. In this area no invertebrates other than corals were observed, and no facilities were available to transport heads of coral to shore for further examination; however, numerous holes were noted in the coral floor where crustaceans, worms and other forms could have lived.

The coral on the shelf was roughly zoned, with the dominant species in the shallower water near the coralline ridge being Pocillopora meandrina, and in the deeper water of the middle and outer shelf, species of Acropora. In the middle and outer portions of the shelf massive heads of Porites lobata were conspicuous. Among the other corals found in this area were all of those reported from the back-ridge trough and some small specimens of Stylaster growing on the undersides of coral heads in twenty feet or more of water. Large areas of the bottom were covered with dead, loose fronds of Acropora.


Inshore Shallow Water
MARINE ASSOCIATIONS
ONOTOA, GILBERT IS.
N
Explanation
Windward Reef
Leeward Reef
Heliopora Flats
Coral Shingle
Mud Flats
Incipient Beachrock
Sand and Beachrock Foreshore
Sand Flats
Turtle Grass
Decadent Coral Reef
1 fathom line (approx.)
10 fathom line (approx.)
2 Miles
Adapted from map made by Preston E. Cloud Jr.
A. H. Banner

II

SHALLOW WATER LAGOON REGIONS AND ADJACENT AREAS

AREAS NOT IN LAGOON.

I. Leeward Island Reef.

This area lies to the lee of the ends of the islands, west and northwest of Tabaurorae and its northern reef. The regions faunistically approach the windward reef but on them there is not a well-developed reef flat and no backridge trough or coralline ridge whatsoever, but instead changes at places quite abruptly into conditions similar to the reef shelf off the windward reef. In water of moderate depths -- two to five feet -- the major elements of the fauna are the same as the backridge trough on the windward reef.

The major exception to these generalities lies in the region northward of the Heliopora flats off Anteuma; here, the conditions are similar to the area within the reef to the west of Abenecnec Island (to be described by Dr. Cloud).

II. Heliopora Flats.

The areas designated as Heliopora Flats are found in a protected region behind the windward reef at the south end of the north island and northwest of the tip of the north island.

The southern Heliopora flat consists of an extensive tide pool about 800 feet in diameter, protected on the oceanside by a coarse coralline boulder ridge, and by elevated sand and boulder covered reefs on the other sides. The bottom of the pool is estimated to be about the 0.0 tidal level, and the water stands about twelve to eighteen inches deep. The bottom is sand. The dominant animal is Heliopora, with one head about every square yard; Porites sp. is perhaps a tenth as plentiful. Other corals, all infrequent, include

Orbicella, Pocillopora, Leptoria. On the exposed sand bottom no animals except Holothuria atra are conspicuous. Other invertebrates are found in two habitats.

A. Under coral heads. Here are found stomatopods (Pseudosquilla ciliata), Tethys, two species of tunicates, four species of holothuroids, *Thais hippocastanum, and several species of brachyuran crabs.

B. In coral heads. Here the dominant forms are crangonid shrimps and small xanthid crabs. Encrusting sponges of various types are common; black colonial tunicates are plentiful; one head only showed numerous small sea anemones. Annelid worms, both Errantia and Sedentaria, are moderately common. Several species of clams, including *Isognomon sp. and *Barbatia tenella, are found between the inner branches of the coral.

The northern Heliopora flat is faunistically similar to the southern, with the same population. However, it shows the transition, on its inner side, between a typical Heliopora flat as described above with infrequent heads of Heliopora reaching from the sand bottom, through a condition where the Heliopora is growing thickly and the top ends were being consolidated by coralline algae, to a consolidated condition like that described in section A-8 of the windward reef. In the labyrinthian passages below the surface consolidation are numerous small fish. On the outer edge these flats gradually change in a moderately deep water coral association with passages between the coral six or more feet deep.

III. Shingle Flats.

These areas of shingle -- flattened and waveworn coral rocks lie in regions where the waves and the currents are strong enough to sweep away the sand. These conditions are found in the passes between the islands, as in the three passes between North Island and South Island, and the two passes west of South Island. The size of the rocks varies with location, being large

where there is an unbroken sweep of the water, as between the windward side of the Abenecnec passes, and gradually changing into fine gravel on the more protected extensions of the current, as to the west end of the southern tip of North Island, which in turn is replaced by the fine sand characteristic of the lagoon. All shingle areas inspected were above the 0.0 tidal zone, and in places extended up to the edge of the terrestrial flora. In some portions of the passes there were developed broad shallow tidal pools, with a bottom of finer rocks or sand.

Without exception these actual pass areas were found to be devoid of larger animals; even the tidal pools appeared lifeless. However, where there was slight protection either from islands or from bars, there was a feeble fauna developed, with some xanthid crabs, a few sponges and heads of Porites in the tidal pools. In the fine gravel zones, transitional between the shingle and the lagoon sand, some life was found in the levels near the zero tide zone. Burrowing into the dead coral reef under these areas were found sipunculids and annelids; in the small shallow tidal pools were found occasional brittle stars, solitary zooanthids and small crabs under the scattered loose boulders.

LAGOON AREAS

IV. Sand Foreshore.

Along the lagoon side of the island the foreshore, from about the two foot tidal level up alternates between fine sand and consolidated beach rock with more areas of beachrock off the northern island and more sand off the southern. Only near the tips of the islands and around smaller islands like Anteuma and Abenecnec are these two characteristic beach formations replaced by coral shingle. The sand foreshore is devoid of life except for occasional ghost crabs Ocypode ceratophthalma the same species that is found much more

plentifully on the windward sand beach.

V. Beach-rock Foreshore.

Alternating with the sand foreshore are areas where the elevated beach-rock of the island's base is exposed by wave action. This slab is eroded on the top surface into the typical cupped pattern, and often is undercut along the lower edge by wave action and possibly solution by fresh water from the island lens. At places, especially in the lower tidal zones, the undercutting has proceeded far enough so that slabs up to several feet or more long have broken off from the base rock and lie free on the substrate of either beach-rock or of sand.

Animal communities in this habitat when the tide is out are subjected to dessication and heat, to rain and especially to the flowing fresh water, common all along the shore; when the tide is in, to moderate wave action (except, possibly during periods of storms from the west when the wave action would be vigorous).

The rocks can be subdivided into four associations:

A. The higher beach-rock area. This is above about the 2.5 foot tidal zone and is almost devoid of life except for *Nerita plicata and Grapsus grapsus, neither as common as on the similar rocks on the windward side of the island.

B. Lower beach-rock area, rocks lying on solid substrate or undercut solid rock. These rocks lie between the 0.0 and 2.5 tidal zones. In them are found burrowing sipunculid worms; near the edges of the rocks are numerous Holothuria atra and less numerous Holothuria monocaria, some colonies of colonial tunicates and some sponges; under them are numerous crabs of at least four species, four or more species of crangonid shrimps, very few hermit crabs, and no worms.

C. Lower beach-rock, rocks lying on sand. These are in the same zone as B above, but lie with the base imbedded in the sand. About their edges is the common Holothuria atra and clusters of zooanthids; in burrows under them in the sand are numerous large worms of the genus Eurythoe and three species of crangonid shrimps.

D. Lower beach-rock, suspended rocks. These, lying with one end on other rocks, leave a large surface underneath open to free circulation of water or air, and protection from the sun and rain. On this surface, hanging down, are hydroid colonies in profusion, and some colonial tunicates, a few sponges.

VI Mud Flats.

In a short narrow area along the middle of the North Island, below the foreshore and behind the incipient beach-rock (VII) there is a mud flat. The height of the mud flat is slightly above the zero tide level. The mud is soft, so that a person walking over it would sink between ankle and knee-deep; slippery with little admixture of sand, and rich in organic matter whose decomposition gives it the characteristic odor of hydrogen sulfide.

In this mud flat proper is only one species visible, the brilliantly colored fiddler crab, living in burrows. In areas transitional between the mud flat and the sand are found some burrows of stomatopods. There were no traces of annelid burrows or of other macroscopic life.

VII Incipient Beach-rock

A small area off middle of the northern island, bounded inshore by the mudflats (VI) and off shore and at the ends by sand flats or turtle grass (VIII and IX), is composed of beach-rock in the process of formation, according to Dr. Cloud. The rock is as firm, or almost as firm as the typical elevated beach rock (V) but its surface, near the zero tide zone, was roughly eroded like the more exposed rock (IV-A).

In protected areas in the rock, as in deeper cusps, in fissures and under the occasional loose rocks are the following snails: *Thais hippocastanum; *Mitra virgata and *M. litterata; *Cymathium chlorostomum and *Conus hebraeus. Under the rocks are numerous hermit crabs. Burrowing into the rock were sipunculoid worms and sea anemones were found in protected locations where they were living in shallow pits that precisely fitted the basal portions of their columns. In shallow but rather long burrows that they have either excavated or taken are the large red-eyed crabs and fiddler crabs; at the entrance of these burrows were vast numbers of Collembola.

VIII Sand Flats.

The most extensive habitat in the lagoon is the sand flat. These flats run from the inshore beach along the three major islands extending as a broad, almost level, flat from the inshore beach outwards for several hundred feet wide to a half mile or more. On the outward edge they either continue as the sand bottom of the lagoon or are covered by turtle grass (IX), or are demarked by a decadent coral reef (X). The portions of this area described below run from about two feet above to several feet below the zero tidal zone. The sand varies from less than an inch thick, covering old coral reef, to at least several feet thick.

The fauna of this zone varies with the depth in the tidal zone, the fineness of sand particles, the amount of wave action, and with the depth of the sand. The differences in the fauna are not well demarked and most often are quantitative rather than qualitative -- the same species present in most areas, but varying in relative abundance. Of course, with the difference in depth the fauna changed markedly; for example, in the highest portion here considered (some tidal pools in the middle tidal zone off Anteuma), the only elements of

the fauna left were the Enteropneustan, Ptychodera, and on the other hand, below the -1.0 tide level solitary heads of coral would reach up above the surrounding sand.

These solitary heads of coral in this area, like those in the Turtle grass area, constituted microenvironments markedly different from the surrounding sand. For that reason they are considered as a separate subdivision below.

A. Sand area proper, fauna:

Porifera: Purple sponge, black sponge (two kinds), orange sponge.

Coelenterata: Zooanthids (corals considered below).

Annelida: Tubeworms with leathery tubes and with sand tubes; two species of Errantia; small and giant sipunculids.

Crustacea: Lysiosquilla maculata; Callianassids, Calappa sp.

Mollusca: (Note: remarkably few traces of living mollusca were found, although dead shells were seen in some areas; this may be attributed to the fact that most of the sand flat molluscs are esteemed as food by the Gilbertese.) Clams, various species including *Cafrarium pectinata, *Tellina crassiplicata, *Tellina sp., *Nautica sp., various species of Mitra, Terebra, Cymathium, Trochus.

Echinodermata:

Holothuria atra (extremely common in some areas, counted at 5-15 per square yard).

Chordata:

Ptychodera sp.

B. Isolated coral heads, fauna:

Porifera: same as above.

Coelenterata: Porites sp. (dominant); Pocillopora damicornis; Acropora servicornis; Orbicella; other corals in lesser numbers.

Pennaria.

Annelida: Tube worms in limy tubes; sipunculids

Crustacea: Crangonids, various species; brachyuran crabs.

Mollusca: Cyprea erosa, *Monetaria moneta, *Barbatia amygdalumtostum.

Chordata: Colonial tunicates.

IX. Turtle Grass

Large areas in the northern part of the lagoon and portions of the southern lagoon are dominated by Turtle Grass (Thallasia sp.) which extends over the sand bottom from water about at the zero tide line or a little above to six or ten feet below the surface. The Turtle Grass, which makes a dense stand like the northern eel-grass (Zostera), seldom grows over a foot or more high; its creeping rhizomes make a dense interwoven mat in the sand substrate. In the southern portion of the lagoon less area is adaptable to the growth of the plant, and in general it is limited to a relatively narrow zone near the shore of the island; in the middle of the lagoon, off the passes between North and South Island and the adjacent areas, and off Tabuarorae and the southwesternmost portion of the lagoon there is no Turtle Grass whatsoever.

The Turtle Grass proper is relatively devoid of invertebrate life. On the fronds of the grass are found black colonial tunicates and occasional sponges of several types; about the bases of the grass are more sponges of the same type and, most abundant in many areas, a papillose green-black holothurian. It was impossible, once digging was started, to dig out the

few burrowing animals detected because of the clouds of fine silt that rendered underwater vision impossible. The burrowing animals, however, are few in number and appeared to be limited to a small squillid (Lysiosquilla) and some burrowing worms.

In the deeper portions of the Turtle Grass beds, especially in the area off the northern island, there appear solitary and separated coral masses, like islands in a sea of grass. These isolated masses are rich in life, both fish and invertebrate. They evidently are made up primarily of Porites, but they are covered in a large extent by other corals like Acropora, Pocillopora, Orbicella, etc. The invertebrate fauna is in general similar to the fauna of coral heads in the sand beach area (VIII-B).

X. Decadent Coral Reef.

In many areas the sand flats grade gradually into a region of dead coral reefs that lie between + 1.0 and - 1.0 tidal level. These areas appear to be those where the wave action and current action is stronger, sweeping the veneer of sand from the harder substrate. They are found to the southeast of Anteuma; off the southern portion of the North Island and the northern portion of the South Island and the passages between; and they are extensively developed off Tabuarorae and in the southwestern portions of the lagoon.

The decadent to dead coral reefs present a variety of habitats for invertebrates: on the hard coral there are places of attachment, protected and unprotected, for sessile forms; in naturally occurring spaces and in burrows in the coral there are places for the smaller invertebrates to hide; in the areas between the heads of coral, either broken off as the reef was growing or subsequently eroded from the reef surface are pockets of sand and gravel to accommodate burrowing forms; these pockets, some of them many feet

long, retain water when the tide is out and provide a tidal pool for the protection of its inhabitants. For this reason the fauna of the area is more diverse than any other area of the lagoon; however, with few exceptions, no elements of the fauna are exceedingly common:

Porifera:	Yellow to red encrusting sponges, several species	Moderately common
	Black, rounded sponge	Uncommon
	Orange upstanding sponge	Uncommon
Coelenterata:		
	Pennaria	Common on undersides of coral overhangs.
	Porites, living	Uncommon
	Pocillopora damicornis	Uncommon
Annelida:		
	Worms in limy tubes, two species	Uncommon
	Burrowing Errantia, 1 specimen	Uncommon
	Sipunculus sp.	Common
Crustacea:		
	Crangon, and other genera	Uncommon
	Brachyuran crabs (other than Portunids)	Uncommon
	(Portunids)	(Moderately common)
	Hermit Crabs	Rare
Gastropoda:		
	*Conus hebraeus	Uncommon
	Conus flavidus	Rare
	*Monetaria moneta	Moderately common
	*Nautica sp.	Rare
	*Mitra virgata	Rare
	Nudibranch	Rare

Pelecypoda:

*Barbatia amygdalumtostum	Uncommon
*Isognomon perna	Common
*Pinctada vulgaris	Common
*Tellina sp.	Rare
*Tellina crassiplicata	Rare

Echinodermata:

Brittle Stars (as in A-2 windward reef)	Common
Linkia sp.	Rare
Holothuria atra	Abundant in tide-pools at inner edge of area (60 in one pool of about 60 square feet); otherwise rare.
Papillose sea cucumber (as in IX above)	Rare

Chordata:

Ptychodera	Rare
Encrusting compound tunicate, three species	Rare to common, according to the species.

III

GILBERTESE UTILIZATION OF INVERTEBRATES

One of the important phases of a study of a native peoples is the study of the food resources available to the people, and of their utilization of these resources. This is especially true of the inhabitants of a coral atoll, where the food resources at best are somewhat limited, and where, on a small dry and overpopulated atoll like Onotoa, these resources may be the deciding factor in social structure and even of life and death.

On Onotoa the population had available three sources of food; the conventional land produce, plant and animal which obviously was inadequate to support the island's population, especially in times of drought; the marine fisheries, apparently the chief source of protein in the native diets and one of the main sources of calories; and finally, the marine invertebrates, which appeared to be at best merely a supplementary source of food, gathered primarily either when fortuitous occasions arose, like low tides at night for the collection of lobsters, or to serve as mere variations in the usual diet of coconut-pandanus-fish.

However, this study will give some indication of the extent that the Onotoans are utilizing most of the available resources as food.

Methods and Limitations of the Study:

This study was carried on to large part when I was immobilized by blood-poisoning. A native assistant was assigned to help me when he was not busy with other jobs; he was willing and cooperative, but the study was inhibited by his most imperfect English and my total lack of Gilbertese; at times an interpreter was used to bridge the gap.

The study, in its original phases, consisted of looking at pictures in illustrated books of marine life. Later, upon finding that that system was inaccurate because of the inability of natives to interpret correctly the illustrations, all information was gathered by showing the natives actual specimens, specimens that were either collected for us by our native assistants or by ourselves.

The study has three major limitations and sources of inaccuracies. First is the probability that we were unable to find all of the foods of the people because we had neither illustrations nor specimens of them, and our informants did not discuss them because of the language limitations. Second because of their "willingness to please" the natives included animals that possibly were not eaten, or that were eaten only under extreme famine conditions. To remove this possibility several natives were checked, one against another, in as many instances as possible. Third is that not all individuals or family groups utilize the invertebrate foods as much as others -- like in our own society some families eat crabs but others would not consider them. Perhaps my informants were not among those who knew and utilized all of the foods found on the reefs and shores of Onotoa. I did observe on some of the food species that there was no agreement as to the native name; for example, I received three native names for the snail Quimalea pomum. This would seem to indicate that it was not a common article of food.

Systematic Account

Scientific Name Native Name	Notes
1. Coelenterata-Scyphozoa (Carybdea alata Reynaud)	These large (10-12") scyphomedusae occurred at a moderate tide slightly
Te Baitari	before the full of the moon; reportedly

they occurred at similar phases of the moon throughout the year. They are gathered on the windward reef by wading women and children who either put them in baskets or string them on pandanus fibers. In preparation the outer layers of jelly are stripped off, the oral and aboral ends removed and only the remaining material -- the muscular coat of the gastro-vascular cavity is saved. The cleaned material is thus 6-8 inches long, 1½ inches broad and about 1/8 inch thick. It is reported that this is boiled to form a rather sticky "soup".

Annelida-Sipunculoidea

2. Sipunculus indicus Peters

Te Ibo

These are found burrowing in sand flats of the lagoon. They are one to two feet long and the diameter of a man's little finger. When the native, usually a man, finds a hole and casting made by the worm he probes the sand behind it with a flexible and sharpened young root of a pandanus; this, when hitting the vertical portion of the worm burrow follows down the tube. When the worm is touched

by the tip of the probe, it is thrust with vigour and penetrates with the introvert into the anterior body pocket, securely holding the worm. The worm is then dug from the tube. The probe is jerked out, rupturing the anterior body wall of the worm. Then the worm is seized by the back end and snapped like a whip, completely eviscerating it and leaving nothing but the thick muscular coat. This is washed and eaten raw, cooked by boiling or dried for future use.

Arthropoda, Crustacea-Stomatopoda

3. Lysiosquilla maculata

Te Waro

This large stomatopod (about 1 foot long) is found only burrowed in the sand in the lagoon. It is caught by both men and women by placing a spear in the sand so that it is in line with the hole; a piece of fish is placed at the entrance of the burrow as a lure, a noise is made to attract its attention, and as the stomatopod comes to the mouth of the burrow to strike the bait, the spear is thrust home. The animal is cooked and all except the viscera under

the carapace is eaten.

4. Pseudosquilla ciliata (and other species)

Te Waro (as above)

All smaller stomatopods when captured are eaten; they run from one to four inches long. The principal source of these stomatopods is under rocks on the windward reef flat, where they are gathered by hand or by small scoop nets together with shrimps, etc. They are gathered principally by women. Method of preparation as in 3 above.

Decapoda

5. Crangon strenuus (Dana)

Teniwarowaro

(Note: this Gilbertese name evidently includes other genera and species of chelate shrimp and lobster-like crustaceans but the only form observed was Crangon strenuus). These range in size from one inch to fourteen inches long and are caught by all members of the family near the back-ridge trough of the windward reef in small nets when torch-fishing. They are boiled and both the cephalothorax and abdomen are eaten.

6. Panulirus pencillatus (Oliver)

Te Ura

This lobster runs from six to eighteen inches long. It is caught along the windward reef by men and women either during the day when the tide is out or

over the reef surface at night, when torch fishing. Dip nets are used for its capture. It is boiled and the abdomen, portions of the cephalothorax, and legs are eaten.

7. Parabaccus antarcticus (Lund)
Te Mnawa

The sand lobster reaches the length of nine inches; it is caught, prepared and eaten in the same way as in 6.

8. Birgus latro
Te Aii

These coconut crabs are entirely terrestrial and are found by day in burrows. They are dug out only by men. When boiled the abdomen and legs are eaten.

9. Geocaroides sp.
Te Manai

These large land crabs are found only on the North ends of both major islands of Onotoa. They are caught by men and women at night by torch light in the middle of the island. They are boiled and eaten like other crabs (see below).

10. (Terrestrial Hermit Crabs)
Te Makauro

These are small terrestrial hermit crabs that live in the shells of Turbo, etc. They are caught either by day or by night, the latter time by torch light. Only children were observed gathering them. They are boiled and the abdomen alone is eaten.

11. Calappa hepatica (L.)
Tennonno

These sand crabs reach the breadth of about 3". They are captured in the sand of the lagoon when the tide is out by feeling for them under the sand with the hands or feet. Everyone helps in their capture. They are boiled and the legs alone are eaten.

12. Charybdis erythrodactyla (Lamark)
Tentabarereki

These crabs are six to eight inches broad across the carapace and found both on the windward reef and in the lagoon. They are gathered by anyone finding them and boiled; the legs and the ventral portion of the cephalothorax is eaten.

13. Carpilius maculatus (L.)
Te Iba Taburimai

These crabs are found only on the windward reef when the tide is out by day or at night by torchfishing; only adults catch them, either by nets or by hand. They are boiled and eaten as above

14. (Unidentified crab)
Te Nikarewerewe

These crabs are about 6-7" across the carapace, and their habitat, mode of capture and preparation are the same as 13.

15. (Red-eyed crab)
Tentababa

These crabs are found high in the intertidal zone on both windward and leeward beaches, underneath beachrock;

they reach the carapace breadth of about 3 inches. Anyone may catch them, and they are gathered by hand and prepared in the same fashion as above.

16. Ocypode ceratophthalma (Pallas) — These "ghost crabs" are found high on the sand beaches on both shores of the islands where they live in burrows; they reach the breadth of 3". Anyone may capture them, either by digging by day or by torching at night with a net. They are boiled and portions attached to the ventral half of the body are eaten.

Te Kauki

17. Zozymus aeneus L. — These crabs are found at night on the windward reef in torch fishing; they are reputedly extremely poisonous in all parts of the body, causing rapid death when eaten. They are never used as food.

Te Kukua

Mollusca, Gastropoda

18. Trochus, all species — These are found along the windward reef; they are gathered by all members of the family, boiled in the shell and the meat is pulled from the shell for eating.

Te Baraitoa

19. Turbo, all species
Te Nimatanin

These are found along the windward reef where they are gathered by all members of the family; they may be prepared or the shell may be broken and the snail eaten raw.

20. Cerithium, all species
Te Bukikakang

These are found in the sand of the lagoon when the tide is out; they are gathered by everyone. The snail is cooked in the shell and the meat removed after cooking; the shells are used for ornamental bands on dancing belts, etc.

23. Lambis, all species
Teneang

These snails are found on coral in the outer portions of the lagoon, in waist deep or deeper water. Only the men gather the snail; it may be eaten raw after breaking the shell or it may be boiled intact with the meat subsequently removed.

24. Nautica sp.
Te Tumara

These are found a few inches under the sand in the lagoon; they are caught by everyone, boiled in the shell and the meat subsequently removed.

25. Monetaria moneta (L.)
Te Burerewa

These are found in both on windward reef and in the lagoon; they are gathered by everyone. The snails are

used only for shell ornaments; they are first boiled and then buried in the sand for two to four weeks, and finally washed in fresh water.

26. Cyprea, various species
Te Kabaua

These also are not eaten, but gathered to be used as shell ornaments. The larger species of cowries are not used at all. Method of preparation is the same as Monetaria moneta (L.) (25).

27. Amphiperas ovum
Te Bure

These shells are not found on Onotoa, but are imported from Abemama to be used as ornaments for the bow and stern of the outrigger canoes, and for decorations in the Maneabas.

28. Nerita plicata
Te Kaban

These snails are found high on the rocks on the windward beaches and to lesser extent on the lagoon beaches; they are gathered by everyone and cooked in the shell.

29. Cymathium sp.
Te Wiaau

These are found on the lagoon beaches at low tide only near Aiaki (the middle of South Island); they are gathered by everyone and boiled in the shell.

30. Bursa bufonia
Te Kamanging

These are found only on the windward reef flat, where they are gathered by everyone; they are boiled in the shell before eating.

31. Charonia tritonis
Te Tauu

This large conch or triton is found along the outer edge of the lagoon on coral in waist deep or deeper water; it is gathered only by men. It is considered poisonous and not eaten; however, the shell is used as a trumpet to announce meetings in the community hall, and the shell, hung upside down, is used as a flask to store coconut oil (the oil is poured out of the syphon, from which it emerges in a small and easily controlled stream).

32. Tonna perdix
Te Tau

This snail is found in the lagoon in water two fathoms or more deep, on coral; it is gathered only by men. Before eating, the animal is boiled in the shell (one old man informed me it was the young of the conch (31) and had the same name).

33. Quimalea pomum
Te Makauro-n Tari

This snail is found in the same habitat and prepared the same way as Tonna perdix (32).

34. Vasum ceramicum
Thais hippocastanum (L.)
Morula granulata Duclos
Te Nimakaka

These species are all found on the windward reef flat, where they may be gathered by men, women or children; they are cooked in the shell. All are known by the same name.

35. Conus, all species
Te Nouo

These species are found variously on the ocean or lagoon side of the island in shallow or deep water; primarily women and children gather them on the windward reef, while only men gather them in the deeper water of the lagoon. While Conus striatus, one of the poison cones, is among those gathered, the Gilbertese seem to have no knowledge of its "sting". All are boiled before eating, and then the shell is broken to withdraw the meat. Another informant called them "Te Nuo Nuo".

36. Pollia undosa
Te Wikakang

These snails are found only on the windward reef flat and gathered by everyone. They are cooked and the meat is then pulled from the shell.

37. Mitra, all species
Terebra, all species
Te Kabinea

These snails are found only buried one to two inches deep in the sand of the lagoon when the tide goes out; they are gathered by all members of the family and boiled in the shell. Both genera have similar habitats and bear the same Gilbertese name.

38. Melampus, all species
Te Kokoti

These species are found only high on rocky beaches on the northwestern and

southwestern islands, where they are gathered only by women and children; the snails are not eaten but the shells are used as ornaments on articles of clothing.

39. (Nudibranch)
Nei Kamanging

This four-inch nudibranch is found on the middle section of the windward reef under rocks; it is gathered by anyone finding it; before being eaten it is boiled for two or three hours.

40. (Nudibranch)
Neireurekia

This is essentially the same as the nudibranch above (39), except before being cooked the visceral mass is removed.

Mollusca; Pelecypoda

41. Pinna atropurpurea
Te Raun

Found only in southern part of lagoon, two fathoms or more deep, partially buried in sand. It is gathered by men only, and boiled before being eaten.

42. Streptopinna saccata
Te Bere

This "clam" is found along lagoon shores in sand, one foot or more deep. Evidently it is not used for food or ornament.

43. Pinctada marginifera

The pearl oyster is found only on the sand bottom of the southwestern lagoon in three or more fathoms of water. It

is gathered by men only. The meat is removed from the shell before it is boiled. Some pearls are found and the shell can be sold but there is no established pearling trade on Onotoa. The shell is used also by the men for ornaments on belts, for earrings and for canoe decorations.

44. Hippopus hippopus

Te Nei Toro - small individuals

Te Aubuna - large individuals

This giant clam is found on both lagoon and ocean reefs from three feet deep to about two fathoms. All sizes, from two or three inch specimens to those about three feet across, are gathered by men for eating. At times they are eaten raw. When fresh, their meat is boiled with water or coconut milk; they may also be dried with salt and kept several months. The large shells are often used as wash basins. Some families make small holding pens of coral along the beach in front of their houses and keep small specimens alive until they grow larger, or until the family is ready to eat them. One family had a pen about four feet square that held ten clams ranging in size from three to twelve inches across.

45. Tridacna cumingi
Tridacna elongata
Te Were

These are the same as Hippopus above (44) excepting for their smaller size -- up to nine inches across in lagoon, three inches across along the ocean.

46. Tridacna squamosa
Te Were Makai

These are the same as Hippopus above (44); size up to about fourteen inches across.

47. Cardium sp.
Te Tuai or
Te Taerake

These cockles are found in the lagoon only slightly under the surface of the sand, in intertidal zone. They are gathered by everyone; the clam is boiled for food and the shell is used as a coconut meat scraper to make baby food.

48. Cardium (Trachycardium) flavum
Te Nikarikiriki

These cockles are found near the surface of the sand in the intertidal zone along the southern island only. They are gathered by everyone and boiled in the shell before being eaten.

49. Cafraum tumidum
Venus clathrata
Te Koikoinanti

These are both found in outer lagoon on coral and not in sand, in about one fathom of water. They are gathered by both men and women diving from canoes. They are removed from the shell before boiling. Both species are referred to by the same name.

50. Pitar (Agriopoma) japonica
Mesodesma striata
Te Katura

Both of these clams are found along islands buried one to two inches deep in the sand high in the intertidal zone. They are gathered by everyone and boiled in their shells before eating.

51. Protothraca staminea
Te Koumara

This clam is found low in the intertidal zone along the lagoon only near the end islands buried up to six inches deep in the sand. It is gathered by women and children and may be either eaten raw or boiled in the shells.

52. Tellina crassiplicata
Te Nikatona

This clam is found buried eight to twelve inches deep in sand in lower intertidal zone off the south and north island and off the south island. It is reported to be about "fished out". It is dug the year around by anyone. It may be eaten raw, boiled after removing from the shell, or salted and dried.

53. Asaphia dichotoma
Tei Koikoi

This clam is found in lagoon sand in lower intertidal zone buried about one foot deep all along the coast except off the middle of the southern island. It is dug only by women and children; it may be eaten raw or boiled in the shell.

54. Asaphis deflorata

Te Bun

This clam is found only at Abemama Island but not on Onotoa nor any other island; it is found low in intertidal zone in sand of the lagoon. On Abemama it is dug by everyone; it may be eaten raw or bioled and is reportedly of excellent taste. The shells were imported to Onotoa to be used as fishing sinkers.

55. Polypus marmoratus

Te Kika

The octopus is one of the principal invertebrate foods of the people. It is caught on both sides of the island in holes under rocks when the tide is out by spearing with short hocked spears. Men, women and children all capture it. All parts of it are eaten except the ink sac. Several methods of preparation are used with it: It can be pounded on a stone without additional salt until soft, and then either boiled in water or coconut milk for several hours; or it can be salted and dried to be kept for at least several months. Before the dried octopus is eaten, it is washed and boiled.

DISCUSSION

It is remarkable that these people did not use certain supposedly edible animals of their region. For example, careful questioning showed no evidence of the use of sea weeds, of sea urchins (quite common around the islands), and of marine annelids like the palolo worm. All three of these constituted relatively important foods for the peoples of Hawaii and Samoa. In addition several other foods used by other peoples were not used on the islands, like the sea anemones eaten by Samoans; however, no large sea anemones were seen about Onotoa.

Several foods on their list, on the other hand, possibly are not too wide spread in their use; this is especially true of the scyphomedusae, the sipunculids (although these are eaten in the Marshalls) and the supposedly poisonous cone shells.

The lagoon reef is not very productive of the edible molluscs; in all of the field work in the intertidal areas of the lagoon no evidences of living clams or edible snails were seen. While it is likely this condition stemmed from overfishing by the concentrated population, it may actually be the result of low productivity of the Onotoa lagoon reefs.

PART II

INVESTIGATION OF THE ICHTHYOFAUNA OF ONOTOA, GILBERT ISLANDS

Onotoa is a small atoll with a relatively high population density; it is quite dry and subject to extended drought. Few food plants can be grown, and even the coconut crop fails at times. Thus, for the Gilbertese on Onotoa, there is a very great dependence on the sea for food.

The methods of fishing are many and varied and involve men, women, and children alike. Fishing is undertaken largely by the men, however, and centers around the use of the native outrigger canoe.

Lacking suitable trees for dugouts, the outriggers in the Southern Gilbert Islands are constructed from Australian plank lumber obtained from Ocean Island. No metal parts are used, the planks and outriggers being lashed in place with a native cord made from retted coconut husk fiber. The outrigger itself is a solid piece of wood and usually made from driftwood.

Not every man owns a canoe, but nearly every family has one or access to one. In the village of Aiaki there are 370 people and 82 canoes.* Fifty-eight of these are good-sized sailing canoes and can be used for trolling outside of the lagoon.

The fisherman who owns a canoe will usually have the following items of fishing gear: a few fishing lines of various sizes, a small assortment of hooks, leader wire of flexible galvanized type, a large shark hook, one or two handmade lures, a flying fish net, a pointed metal rod with a wooden handle for gaffing large fish, a knife, and swim goggles. Most of the fishermen own a fish spear with rubber sling. Many families have eel traps and small nets for torch fishing. Some have eel snares, fish traps, beach seines, and fine-mesh nets for small fish.

*This information, as well as certain other facts in this report, was supplied by Dr. Ward Goodenough.

A cooperative store is located on the atoll and is supplied infrequently from Tarawa. It usually has hooks and fish line for sale. Normal-sized hooks are quite inexpensive, ranging in price from $\frac{1}{4}$ to $1\frac{1}{2}$ pennies. The large shark hooks, when in stock, cost 2 shillings 6 pence (30¢). Heavy fishing line, of sufficient length for one trolling line, costs 5 shillings.

The Gilbertese can earn very little money; hence they can buy very few of the preferred manufactured items of fishing gear. Copra and various items of native handicraft made from pandanus leaf fiber are the principal sources of income. Each year about 60 men from Onotoa are taken to Ocean Island where they work as laborers and by their standards are well paid. On their return they customarily bring with them such things as wire, old inner tubes, metal rods, pieces of lead, and glass, all of which are important in their making of fishing gear.

There are many different kinds of fishes which serve as food for the Gilbertese, and frequently special methods of fishing are utilized for certain species or groups of species. Usually these methods are standard from fisherman to fisherman, but some individual variation does, of course, exist. In some cases a family or individual may have an efficient mean of catching fish which is kept secret. The description of the various methods as given below represent the standard ways of procuring food fishes on Onotoa.

Trolling: Sailing canoes are used for trolling which may be undertaken in the lagoon, but the usual site is in deep water just outside of the west reef of the atoll, especially the region where there is a large westward projection of this reef. At most anytime, but especially in the morning, one can see numerous sailing canoes trolling back and forth beyond the reef. These canoes may be operated by a single man or by two persons. If there are two persons, they are usually of the same family, as father and son. Women may help their husbands when trolling, but this is not a common occurrence.

Trolling speed is highly variable depending on the wind, but generally no difficulty is had in attaining speeds sufficiently great with these fleet craft. In fact, it would seem that too often the contrary occurs; that is, that good trolling speed is exceeded.

The lures which are used are commonly of three types. A hook may have chicken feathers tied directly to it. Such a lure is used for smaller fish such as the small tuna, Euthynnus yaito. There may be a lure consisting of a piece of metal, usually lead, in which there is a hole through which the leader wire is run. The back part of the metal is notched for the attachment of feathers. The hook is attached to the leader wire and is always single. The third type of lure is made from an elongate, well-polished piece of pearl shell. The hook is attached directly to the piece of shell, and feathers may or may not be added.

The use of whole fish for trolling is a common practice, mullet and flying fish being the usual bait species. Mullets are netted in ponds or close to shore in the lagoon, and flying fishes are taken with dip nets at night. The bait fish is attached to the hook by locating the eye of the hook in the mouth and the barbed end up through the back so it is just exposed on the dorsal surface. The eyes of the fish are then removed, and coconut husk fiber is used to lash through the orbits to the eye of the hook.

Fishes which are taken when trolling at the surface in deep water are: Euthynnus yaito, Acanthocybium solandri, Istiophorus gladius, Elagatis bipinnulatus, Katsuwonus pelamis, Neothunnus macropterus, and at least one other unidentified species of tuna. Swordfishes are occasionally caught. The dolphin, Coryphaena hippurus, is rarely taken. Nearer the reef, species of Caranx and Sphyraena are caught.

When large-sized fishes are hooked, they are gaffed and their heads beaten with a wooden club before being brought into the canoe.

Spearing: Formerly a long wooden spear with a metal point lashed at one end was employed. This was jabbed at fish while swimming underwater. Now, the common method involves a simple elastic sling device and a steel rod of about ¼ inch diameter and five or six feet in length. The sling consists of a piece of truck tire inner tube or a section of bicycle inner tube to which a loop of sturdy cloth is tied at one end and a loop of cord at the other. The metal rod has a notch at one end and is sharpened to a point at the other. There is no folding-type barb, but there may be a small oblique cut made in the rod near the point and the section of metal away from the point bent slightly outward. The thumb of the left hand is placed through the loop of cloth and the notch of the spear engaged in the cord. The notched end of the spear is then drawn back with the right hand, bow and arrow fashion, and the spear is guided as it is launched by the thumb and fingers of the left hand. The spear-fisherman wears small goggles which he makes for himself from local wood and glass obtained from Ocean Island. The goggles are tied on behind the head with heavy string. The final item of spearing accouterment is an optional one and consists of a piece of cord on which the fish are strung. The fish are suspended from the back, the cord being tied around the waist. In swimming the frog kick is used and the fish are approached very cautiously, all sharp movements being avoided. A spear can be shot for a horizontal distance greater than 25 feet but is not very effective beyond a distance of 6 feet or so because of reduced accuracy. Spearing is undertaken in both the lagoon and on the sea side. Generally the lagoon is preferred for there is no heavy surf with which to contend. In the lagoon the fisherman usually

sails or paddles his canoe out to a suitable area. It is anchored with a heavy stone or tied directly to a coral knoll. A paddle or piece of buoyant wood is tied to the anchor line below the surface to prevent the line from catching on coral and chafing.

Spearing fish is a very important method of fishing. It is utilized mostly by the younger men, some of whom prefer it to any other means of obtaining fish. Among those fishes most sought are members of the following genera: Caranx, Scarus, Lutianus, Myripristis, Holocentrus, Acanthurus (especially A. nigricans and A. triostegus), Ctenochaetus, Gymnothorax, Cephalopholis, and Epinephelus.

Shark Fishing: Very strong line, wire leader made from smaller strands of wire crudely twisted together, and a large heavy hook comprise the usual tackle for shark fishing. The hook is usuallya purchased commercial product, but it may be made by hand from steel rod, in which case there is no barb but the tip of the hook is strongly recurved. Fishing may be engaged in from canoes drifting well out at sea. Whole fish is the usual bait, the favorite being the small tuna, Euthynnus yaito, which is caught by trolling immediately prior to the actual fishing for sharks. If the bait fish is alive, it is hooked carefully through the gill openings; if dead it may be tied securely to the hook with coconut husk fiber in a variety of ways. The line is paid out to windward and remains near the surface. Often several heavy shells (Lambis truncata) are tied to a second line which is lowered a few feet below the surface and kept in constant motion. The noise of the shells knocking together supposedly attracts sharks. Some fishermen cut fresh fish into fine pieces and disperse this in the water whereupon the much-discussed power of blood to attract sharks is brought into operation. This surface fishing often

results in the taking of large pelagic fishes such as swordfishes, wahoo, and yellowfin tuna, as well as sharks.

More commonly shark fishing is undertaken over shallow reef areas with a weighted line. Whole fish or cut fish is the usual bait. The sharks taken in reef areas are smaller species, generally, such as the white tip and the black tip.

The flesh of the shark is highly esteemed by the Gilbertese, many of whom actually prefer it to tuna and other fish. It is usually prepared by slicing into sections and roasting in a pit in the ground. Sometimes the flesh is salted and dried in the sun and ultimately eaten without cooking. Still other times it is boiled in sea water.

Night Fishing for Flying Fish: The sailing canoe and at least two persons are required in fishing for flying fish. If there are but two persons, one holds coconut frond torches while the other steers the vessel and works a dip net. Fishing is done outside the reef while moving at ordinary sailing speed. There are usually about eight or ten torches at hand, made from dried coconut leaves lashed in bundles about seven feet long. The first torch is lighted with matches or by striking flint and steel over dried coconut husk. Each subsequent torch is lighted from the previous one just as the latter is about to burn out. The helmsman (and fisherman) generally wears a woven coconut hat to shade his eyes from the torch light. His dip net is elliptical in shape, about two feet in its greatest diameter. The wooden handle is at least twelve feet in length.

The flying fish are attracted to the torch light and skitter about the canoe, some striking the side of it quite resoundingly. The fish are usually caught at the surface but occasionally are picked right out the air by an alert fisherman. When the fish are on the surface the net is dropped directly over them instead of scooping from the side. Usually the netting

operation takes place on the leeward side of the canoe (the side without the outrigger), but the more skillful fishermen extend their range to the water to the stern and the windward side aft of the outrigger.

The only flying fishes observed taken at the atoll were of genus Cypselurus. Most of these were of good size, reaching a maximum of about 15 inches in length. Occasionally some half-beaks were netted.

Hook and Line: The Gilbertese fish with hook and line from canoe, from shore, or while standing in shallow water. A pole may or may not be employed. No use of set lines of any sort was observed. Usually the fisherman handles but a single line which contains but one or a very few hooks due to the great chance of loss of tackle on coral.

Fishing from a canoe takes place in the lagoon but usually over reef areas or near large coral heads. Instead of having a sinker permanently attached to the line, a stone is often loosely tied with a slip knot and the line is then lowered to the desired depth where the stone is released by a sudden jerk of the line. A great variety of fishes are taken but predominantly lutianids, labrids, carangids, serranids, balistids, and scarids.

When fishing from shore on the lagoon side of the atoll, the fishermen (frequently in this case women and children) generally wade well out into the water. Their catch usually includes small Caranx spp. and Gerres sp. and occasionally lutianids.

At low tide fishing with hook and line may be carried on in the surge channels of the reef on the seaside of the atoll. Here a pole is a great asset to the fishermen. These may be made from bamboo obtained from Ocean Island or from a local plant, Guettarda. The pole varies in length from 5 to 12 feet. The usual bait is land hermit crabs which have been removed from their gastropod shells. No sinker is used. The fishes which are most often

taken are Cirrhitus sp., Thalassoma spp., Halichoeres sp., Abudefduf spp., and Lutianus sp. These are small carnivorous fishes which occupy the special surge channel habitat.

No deep water hand line fishing was observed, but interviews with fishermen revealed that a few apparently fish to a depth as great as 100 fathoms from a canoe outside of the reef. The average Gilbertese does not have sufficient line for this or would not want to risk the loss of so much line. The fish which is most sought from the deeper water seems from native description to be the oil fish or escolar (Ruvettus pretiosus).

Torch Fishing: The equipment for this means of catching fish consists of coconut frond torches of the type described for flying fish fishing, a basket woven from coconut leaves, and either a short-handled dip net or a long knife. One man does the fishing, but customarily is followed by a second person who carries extra torches. Fishing may take place in the lagoon or on the sea side on the reef. The preferred site for torch fishing is the back ridge trough, and for this, low tide is a necessity. The water in the back ridge trough at this time is about waist deep. As the fisherman walks along he carries the torch in one hand, the knife or net in the other. The basket for the fish is slung from his shoulder and hangs at his side. Light from the torch is quite bright and fish are readily seen for the water is clear except when an unusually heavy surf is running. Usually a fish can be approached without difficulty and either scooped up with the net or cut with a rapid downward stroke of the knife. Fishes commonly caught by this method include: Cirrhitus sp., Lutianus sp., Monotaxis grandoculis, Acanthurus triostegus, Myripristis spp., Holocentrus spp., Parupeneus sp., Gymnothorax spp. belonids, and mugilids. They are ordinarily eaten immediately after the fishing operation is completed; they are roasted without cleaning in beds of hot coals.

Nets: The simplest type of net is the dip net such as employed in torch fishing. This net may also be used in a fishing operation during the day at low tide. The location is a surge channel. At Onotoa the surge channels are narrow, irregular indentations into the reef averaging about six feet in width and ten feet in depth. The water in these channels is in constant motion, and visibility from the surface or in the channel is poor because of the foam from the breakers. One man uses a coconut frond to drive fish in the channel toward a good vantage point where a second man keeps his dip net in the water. Both men stand on the reef beside the channel. This method of fishing is not a common one.

Small seines of about two fathom length and four or five feet in depth are often used. A seine may be operated by just two persons, each holding a vertical pole at each end, but usually several other persons assist by driving fish toward the net. Frequently a woven line of coconut fronds serves as an extension of the seine from one or both ends. At low tide on the reef the back ridge trough is a region which is commonly seined. One such operation was closely observed. A man, his wife, and two boys were the participants. The fish they hunted was a good-sized scarid which comes up into the shallow water on the reef in small schools. The fishermen endeavored to get between the fish and the open sea. Sometimes this involved actual running with the seine in the shallow water; at other times slow cautious movements were necessary. When the fish were cut off and tried to elude the seine, they were herded by the boys toward the net with coconut palm fronds and by splashing and throwing stones. Many large parrot fish were caught and some surgeon fish (Acanthurus triostegus) and damsel fish (Abudefduf sp.) were taken. The fishes were rendered inactive by biting the dorsal part of the skull and were strung

by cord through the eyes to one of the poles of the seine. This one fishing operation lasted several hours and covered a distance of about two miles.

In the lagoon small seines are used over shallow sandy areas and the fishes caught include Gerres sp., small Caranx sp., mullets (Mugilidae), and goatfishes (Mullidae). Here the seining is very often the work of women and children.

Small seines may be imported cotton products or may be made from local material.

Some large beach seines are owned collectively by entire villages. Each village usually has but one such seine. However, the largest village, Aiaki, is divided into two sections and each owns a seine. These are made of coconut husk fiber and may be as long as thirty fathoms. Shells are used as weights on the foot rope and pieces of a local wood (Scaevola) strung along the float line. These seines are used only in the lagoon, and their operation involves many individuals. One is designated the leader, and he directs the operation by hand signals, for noise is kept to a minimum. One end of the seine is worked out from shore in a large semicircle until it is again brought to shore at which time both ends are hauled up on the beach. The same fishes are caught with these large seines as listed above for smaller seines in the lagoon plus a few others such as lutianids. At night more larger fishes are caught, including small sharks.

One other type of net is used for a very special kind of fishing. This is a fine mesh netting (generally mosquito netting) with a slight bag and supported at four corners with poles. The net is suspended horizontally in the water between two canoes, men or women from one canoe holding two of the poles vertically in the water while those in the other canoe handle the other two poles. The area over the net is chummed with bits of fish. Small fishes

of genus Caesio are caught when they swim over the netting by a rapid pulling up of the four poles. These fishes occur in the lagoon in numbers great enough for such fishing only once every ten years or so. They tend to form small schools over coral heads in the lagoon. They are dried on coconut or pandanus mats out in the sun and stored in tight-lid containers, where they remain well-preserved for many years. The flesh is red in color when dried and considered a great delicacy.

Traps: Two types of traps are made from lashing small sticks together. The most common in use is the eel trap. This consistently has the configuration of a house (rectangular with a sloping roof), roughly three feet long and a foot and a half wide. At one end a hole of three-inch diameter can be seen. This extends, cylinder-like, toward the middle of the trap where it is narrowed by side flaps of woven coconut fiber. This trap is baited. It is set by lowering with a line from a canoe in water up to ten fathoms deep. The species of eels taken are mostly of genus Gymnothorax. A small trap door in the "roof" affords a means of removing the eels.

The second type of trap has the appearance of a small quonset hut. Size is more variable than the eel trap, but it is generally not more than three feet long. It is set by diving in water up to about three fathoms in depth. It is placed in such a manner in the coral that it can be concealed by addition of a few stones or pieces of coral. The entrance to the trap, which is similar to that of the eel trap, is kept free. This trap is not baited and is designed to capture reef fishes which tend to seek refuge under rocks or ledges of coral. These include a number of acanthurids like Ctenochaetus strigosus, scarids, holocentrids, and lutianids. A covered opening on the opposite end to the trap entrance is used to remove the fish. Such fish traps do not seem tobe utilized very frequently.

Another type of fish trap which is of considerable importance is the stone trap. These are found in the lagoon, on the reef, and in shallow passes between islands. They are constructed by piling stones into a long, low wall which encloses a large, roughly rectangular area. The wall is usually about a foot and a half high and well covered by water at high tide. As the tide lowers the top of the wall is exposed thus isolating a body of water within the trap. With further lowering of the tide the water within the trap decreases and the fish are concentrated to an extent where they may be seined or picked up by hand. The same species are taken by stone trap as were mentioned for the lagoon and reef seining operations except for mullets which escape by jumping over the wall. On the sea side the wall is occasionally broken in places when surf is heavy, and must be repaired. Here, however, red coralline algae tends to cement stone of the trap together and must greatly reduce the maintenance of the trap wall.

Tide Pool Fishing: Three means of collecting fishes from very shallow water are included here. First there is the collection of small tide pool fish by hand which is usually the task of women and children. By far the most important fish taken is the young of Epinephelus merra which are very abundant in tide pools and in shallow water lagoon areas. These are dried in the sun and eaten without cooking.

A species of moray eel, Gymnothorax picta, occurs well up on the reef flat on the sea side of the islands of the atoll. A method for capturing this species was observed. At low tide the fisherman walks over the reef, equipped with a basket with a lid and two metal rods about two feet long. One is sharpened and the other is hooked at the end. Boulders are rolled over and every likely hole in the coral is inspected with the rods, and the morays, when located, are pulled from their holes with the hooked rod.

Another method for catching eels is a simple snare device. A stick about two feet long is baited at the end with a piece of fish. A second stick has a noose which may be drawn tight.
This is placed around a hole which looks like a likely dwelling for a moray. The bait is held just outside the noose. As the moray lunges for the bait the noose is pulled tightly around his body behind the head. This is a very old fishing method but still used today. Usually it takes place on the reef flat at low tide in the surge channel area. The same method may be used in the lagoon in deeper water by diving.

Pisciculture: The milkfish, Chanos chanos, was at one time actively reared in ponds, especially one fairly large isolated body of water in the complex of tiny islands in the southern part of the atoll. The young of this species were periodically seined from outside areas and transferred to the ponds, since adults will not breed there. Such a practice has been more or less discontinued for some years.

Poisonous Fishes: Numerous interviews with groups of natives concerning the presence of fish in the atoll waters with poisonous flesh were undertaken. The only fishes which were considered poisonous at this time were the puffers and then only the internal organs, especially the gonads, were toxic. In view of the prevalence of poisonous forms throughout the whole Pacific area, it was hard to believe that there was no such problem at Onotoa. The natives were observed catching, preparing, and eating many species known to be poisonous elsewhere. Interviews did reveal, however, that a certain section of the reef near the northern part of the atoll harbored poisonous fishes for several years but for the last two years fish taken from there have not been toxic.

Fishes with poisonous spines do occur in the area, notably sting rays,

siganids, and certain scorpaenids like Pterois. The stone fish, Synancea verrucosa, was not collected but very probably occurs on Onotoa. It is reported from Tarawa.

Attacks by Sharks: Several discussions with natives were initiated in respect to this subject. Only five cases of attack by sharks on men were recalled - even by the older Gilbertese. These involved large sharks and not the common smaller forms near the reef. The natives swim around these smaller sharks without any noticeable fear. Sufficient information was not secured to identify the larger, dangerous species of sharks.

Fishing Regulations: Before the white man came to the Gilbert Islands sections of the reef flat and water areas of the lagoon were owned by men who retained exclusive rights to fish in these areas. A man who fished in another man's region risked violent punitive measures by the owner. Missionaries arrived in the Gilbert Islands around 1850 and tended to break up these holdings. When the British took over the islands as a Protectorate in 1892, the system of owning reef and lagoon areas was soon completely eliminated.

Today by native law one regulation of this sort exists. No man can fish in the vicinity of another man's stone fish trap at or near low tide.

One other interesting law exists. On the rare occasions when Caesio sp. (the special fishing method for this fish was previously described) occur in the lagoon in large numbers, no flying fish fishing is allowed. It is believed that the light from the torches will frighten Caesio away. A fine of three shillings is imposed on any man caught fishing for flying fish during this time.

No restrictions were noted concerning size limits. As far as known no species of fish were ever reserved for special individuals or occasions.

Preserving of Fish: Most of the fish is eaten fresh, the fisherman usually catching only enough for immediate family use. When more is caught, it is cut into thin pieces and dried in the sun. It may be cooked prior to drying. Usually it is not salted, and rarely is any of the catch smoked.

Abundance of Fish: No collection of catch statistics nor direct measurement of fishing effort was made, but the fishing effort on Onotoa, by atoll standards, seems high. This is due to the relatively high population and the emphasis on fishing. Nevertheless, it is doubted if any serious depletion of fish stocks has taken place, even for reef fishes. There are, however, more reef fishes to be seen by underwater observation in outlying parts of the atoll away from usual fishing activity and in other atolls with smaller native populations. Also, in the latter regions the fishes may be approached much more readily when swimming underwater.

Still, today, the Onotoan fisherman can obtain all the fish he needs in a relatively short period of time, at most two or three hours.

FISH COLLECTION ON ONOTOA

The majority of fishes which were collected during the two month's stay on Onotoa were taken with powdered cubé or derris root containing rotenone, the active poisonous ingredient. Ten successful poison stations were executed with the two hundred pounds of cubé root which was on hand.

Nearly 120 species were added to the collection by spearfishing, though many of these turned up in poison stations as well. Spearing is a highly selective means of getting fish and useful in obtaining fishes such as parrotfishes (scaridae) which are not easily poisoned. But this method has the obvious disadvantage of mutilation of specimens, and one usually fails to obtain a sufficient number of specimens of any one species in this way for ordinary

taxonomic purposes.

Considerable difficulty was experienced in procuring fishes from the Gilbertese which they had caught and which were destined for their dinner tables. This was especially true when the natives observed that most of the fish which was purchased from them did not end up as a component of the expedition's diet. Fish, they must have reasoned, should be put to but one use, food. Nevertheless, some valuable additions to the fish collection were made through purchases and trading, particularly with the children. Very material aid was obtained from the natives in recovering fishes at poison stations.

A few fishes were caught with hook and line, with use of nets, and by hand in tide pools.

Field work was dominated by making the collection of fishes, since description of the fish fauna of a new area must necessarily precede ecological studies; nevertheless, some ecological work was done. A description was made of the areas where fishes were collected. This, coupled with extensive underwater observations, made it possible to identify a type habitat for many of the species. Of course, specific habitats are difficult to delimit for marine fishes, and even when one manages with fair assurance to pinpoint a fish in a certain environment, it often pops up in an altogether different one.

Analysis of the stomach contents of fishes was made when a surplus of specimens was available. Such data were obtained for about fifty species; however, there were usually insufficient numbers of any one species examined to demonstrate total variability of food habits. Food studies which were made on fishes taken by poisoning were complicated by an unanticipated factor. Many of the fishes which are normally non-piscivorous were found to be opportunists and fed upon smaller poisoned fishes before they, in turn, succumbed

to the poison. This source of error was more or less compensated for by disregarding all recently-eaten fishes which could logically have been killed by the rotenone.

A reef transect for fishes was attempted from shore to "lithothamnion" ridge during a period of exceptional low tides and with the last of the supply of rotenone. When approximately half completed, storm conditions precluded the completion of this project.

The local Gilbertese names for fishes were recorded. It was found that smaller species frequently were not named. In fact, poisoning produced many fishes which the natives had never seen, and for which they obviously had no names. It was interesting to note how groups of similar species were often given collective names which paralleled the families of ichthyological nomenclature. Acanthurids, balistids, tetraodonts, and chaetodonts are examples; the names te riba, te bubu, te buni, te ibaba can be applied freely to nearly any fish within these respective families. The more distinctive or common members of these groups generally have more definite names, though often the above names remain as roots. Acanthurus achilles, for example, is called te ribataukarawa. There was not always complete agreement among the Gilbertese for their names of fishes, especially for the rare species.

The fish collection from Onotoa comprises about 325 species. These still bear field identifications to a large extent, and thus no taxonomic report can be presented at this time. The following is a breakdown of the collection on a family basis and will serve to give some idea of its extent and the predominance of certain families over others:

Family	Number of Species
Acanthuridae	15
Antennaridae	2
Apogonidae	10

Atherinidae	1
Aulostomidae	1
Balistidae	6
Belonidae	2
Blenniidae	16
Bothidae	1
Brotulidae	2
Conthigasteridae	3
Caracanthidae	2
Carangidae	5
Carapidae	2
Chaetodontidae	17
Chanidae	1
Cirrhitidae	6
Echelidae	2
Echidnidae	26
Eleotridae	6
Exocoetidae	2
Fistularidae	1
Gerridae	1
Gobiidae	10
Hemiramphidae	2
Holocentridae	16
Istiophoridae	1
Labridae	34
Lutianidae	17
Monocanthidae	4
Moringuidae	3

Mugilidae	3
Mullidae	6
Ophichthyidae	1
Ostraciidae	1
Parapercidae	1
Permpheridae	1
Platycephalidae	1
Pleuronectidae	1
Pomacentridae	29
Priacanthidae	1
Pseudochromidae	4
Scaridae	22
Scorpaenidae	8
Seriolidae	1
Serranidae	13
Siganidae	2
Sparidae	1
Sphyraenidae	1
Syngnathidae	2
Synodontidae	2
Tetraodontidae	3
Thunnidae	3
Zanclidae	1

At least twenty-five additional species were observed underwater but were not taken. Many of these were provisionally identified.

Only three sharks were captured. Some rays were seen but were not taken.

An opportunity provided itself to test the efficacy of copper acetate as a shark repellent. The following is taken directly from my field notes: "Two sharks (Triaenodon obesus) were observed by Dr. Banner and myself slowly circling an area where it is believed a speared (and hence bleeding) fish was seeking refuge in a hole in the coral. The water was about eight feet deep and fairly clear. The sharks were estimated at 4½ and 5½ feet in length. The smaller shark was seen on two occasions to stick his head down the hole, thus exposing his body vertically in the water. From time to time the sharks would leave the area, either singly or together, but always they returned. They were never observed to swim rapidly. A small tin of copper acetate crystals was dispensed by Dr. Banner in a circle of about twenty-five feet in diameter around the area. At this time the sharks were absent. The smaller shark was then observed to approach the area but not enter it. The larger shark, on reaching the cloudy area where the acetate had precipited, turned sharply around and swam very swiftly away. Within at least the next ten minutes neither shark was seen at all."

Over two hundred color photographs of fishes were taken with 35 mm Kodacolor film. Most of these were satisfactory.

ATOLL RESEARCH BULLETIN

No. 14

Description of Koyangel Atoll, Palau Islands

by J. L. Gressitt

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DESCRIPTION OF KAYANGEL ATOLL, PALAU ISLANDS

By J. L. Gressitt
Pacific Science Board

Kayangel Atoll is the northernmost land area of the Palau Archipelago in the western Caroline Islands, except for Ngaruangl, a sand bank on an incipient atoll to its north. There are no other atolls within 150 miles. Kayangel is separated from Babelthuap, the largest island of the Palaus and a volcanic island, by about twenty miles of water. Between, there are only two small islands, Ngaregur and Ngarekelau, just north of Babelthuap, and the large "V"-shaped Kossol Reef pointing towards Kayangel, in the middle of the intervening space. Other reefs extend somewhat north of Babelthuap to the west, particularly, and also to the east. From the hill above Olei at the north end of Babelthuap, Kayangel may be seen as if it consisted of a small islet at the left and a long one to the right (east).

Kayangel is a small atoll, with a north-south diameter of less than three and one-half miles and an east-west diameter of only two miles. The atoll consists of an almost complete circle of reef, with four islets. The latter are all on the east side, occupying a little less than the eastern half of the perimeter. The islets decrease markedly, and somewhat geometrically, in size, proceeding from north to south. The entrance to the lagoon is not very distinct, and is shallow. It is located on the west side a little north of the center, and west of the pier at the middle of the main island. It consists of a sand-bottomed break in the reef a number of yards wide and extending obliquely inward in a northeast direction. It is only one to two fathoms deep at low tide and is dotted with coral heeds of varying size, so that passage of craft larger than canoes must be undertaken at very slow speed, and is very dangerous in rough weather. At high tide in good weather a craft of less than one fathom draft can pass over the reef at the south end, one hundred yards west of Gorak Islet.

The lagoon is largely of sand bottom and varies from very shallow to a few fathoms deep. Most of the southeastern one-third of the lagoon is less than two fathoms deep and has large scattered coral heads except in the shallower parts. In some shallow areas east of the center or near the center of the main island stag-horn coral grows on the bottom. Quite a bit of it has been broken by canoes or fishing operations. In the central and northern parts of the lagoon the water is deeper with the coral heads less visible. In the southwestern part the coral heads are quite large and widely separated, and the water a few fathoms deep. In the western part the coral heads are closer and the water shallower approaching the inlet.

The reef forming the atoll is, in general not very wide on the west side, and the water becomes deep rather soon, particularly near the south end. At several points there are large blocks of coral rock which have been washed up onto the reef, and two of these on the southwestern part are even visible at moderately high tide. At lowest tide the reef is visible at a number of points in the different parts. On the east side, seaward of the islets, there is for the most part a fairly flat platform exposed at low tide. It consists of more or less solid coral limestone, marked in part with tidal pools of a shallow nature and with old coral structures generally evident. At some points, particularly near the ends of the islets, masses of coral rocks or gravel have been washed up. The sea bottom slopes off at an initial grade of 10-25 degrees.

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The intervals between the islets are rough and rocky, with tilted coral slabs in part, on the seaward side, and sandy on the lagoon side. At lowest tide it is possible to walk between the two northern and the two southern islets largely on exposed sand, with only short distances to wade in shallow water. The route between the two northern islets is over very fine white sand in a large broad arc curving into the lagoon, whereas between the two southern islets it is almost direct but the sand is mixed with coral gravel in part. The water is deeper on the lagoon side between the middle islets, and the distance is greater and there is some coral growth. Near the south end of the lagoon side of the second island (Ngariungs) are some eroded mushroom-shaped blocks of coral rock exposed at low tide, some of which have fallen over.

The east or seaward shores of the islets consist for the most part of fairly narrow sloping beaches of rough coral gravel or accumulations of coral rocks with almost no sand. On the main island, however, there is a higher proportion of sand on the east coast, even to pure sand or only partially mixed with broken coral gravel. The west or lagoon shores of the islets are almost entirely of sand beaches, though the sand is rather coarse and mixed with coral fragments in part. Near the north end of the lagoon side of the second island (Ngariungs) there is an area of solid coral rock, or beach sandstone, mostly of irregular, flat or sloping surfaces, with some up-tilted slabs or boulders. The ends of the islets are more rocky and have narrower beaches. The north ends are largely gravelly. The south ends of the second and fourth islets are largely rocky, that of the main islet is sandy with some rocks or gravel, and the south end of the third islet (Ngarapalas) is largely sandy. There is at least some sand at the north end of the north island.

Kayangel Atoll apparently has a rather wet climate, with an estimated annual rainfall of perhaps 150 inches. The four islets are almost entirely covered with vegetation. This includes about 13,000 coconut palms in the less than one square mile of land area, but also quite a bit of apparently natural vegetation. The human population in 1951 was 124, the village being on the main island. Coconut palms grow on all four islets, but taro, breadfruit and other crops only on the main island, except for a little near the north end of Ngariungs Islet. The altitude above high tide water level is largely from three or six feet except where it is raised a few feet higher by the nests of megapode birds or by artificial coral-slab platforms of houses or graves.

The main island, or Ngajangel, the northernmost, is the largest. It is about one and one-third miles long and about one-quarter to two-fifths of a mile in width, being narrower towards the south end. The pier is located near the middle of the lagoon side. The village extends in a double row of widely spaced houses along a pair of parallel avenues near the lagoon shore for about one-third the length of the island from a little north of the pier to the beginning of the south quarter, where the school and the old cemetery are located. Near the pier and the cemetery there are some very large Calophyllum inophyllum trees with platforms of coral slabs built up around their trunks. Along the beach in the village area are some canoe sheds, including some large ones near the pier, and a number of small copra drying sheds. Along the beach grow Hibiscus tiliaceus, Barringtonia, Messerschmidia, Scaevola, Hernandia, Thespesia and other common strand plants. Behind these tower coconut palms in regular rows, spaced about five yards apart. The palms were planted by the Germans and are about 60 years old and 50-60 feet tall. The trunk of most of them has an orange colored alga growing on the surface. The palms are apparently in good

condition

condition, with fair yields. They grow almost the entire length of the west side of the island, except near the north end. The east half of the island has some younger coconut groves, but they are mostly limited in area and do not reach the east coast. The remaining area is largely of mixed second growth, except for the cultivated areas, and includes some very large trees (one with almost creamy white bark) and some rather dense growth. The north end appears more natural and less disturbed, and has quite a variety of plants. Pandanus tectorius grows along the entire east coast, as well as elsewhere, in places forming rather dense tangles.

In the northcentral, broadest part of the main island are the taro beds, consisting almost entirely of the large false taro (Cyrtosperma chamissonis, "b'rock") growing in large submerged areas. Some small areas of ordinary taro (Colocasia esculenta, "ku-kao") are found nearer the village. Some cassava (tapioca) fields are scattered in patches in yards in the village, and also in clearings in the eastern half of the island. Breadfruit trees and banana and papaya plants grow largely in the neighborhood of the houses, but there are also some in scattered clearings, one even near the southeastern shore of the island, which is largely grown up with very tall weeds. There are a number of lime trees growing in the village, producing a surplus of fruit. Betel palms are rather scarce. A few dwarf coconut palms grow in yards in the southern part of the village.

Just north of the village is the principal water supply for the community. It consists of a pool of slightly brackish water about three yards square, walled by large squared blocks of coral rock. The water is frequently at about the same level as high tide. Toads (Bufo marinus) introduced since the war to control monitor lizards (Varanus indicus), are numerous in the pool and contaminate it by dying in the water or in crevices between the rocks. (The monitor lizards are controlled by feeding upon the toads and being killed by their poison glands.) The introduction was an unfortunate one, since not only do the toads pollute the scarce water supply, but the monitor lizards are predators upon the coconut rhinoceros beetle, recently introduced into Kayangel. The introduction was made because the monitor lizards prey upon chickens, but the coconut palm is far more important to the Palauans than are their chickens. In addition to the above pool there are some smaller, less elaborate pits dug for water, which generally contain a few inches of water.

The second island, Ngariungs, is both narrower and shorter than Ngayangel. It likewise tapers somewhat from north to south. Just over one hundred yards from the north end of the islet is a shallow inlet from the east coast which widens in the middle of the island and reaches to within 25 yards of the western shore. Its floor is partly of coral rock and partly of mud or sand, and it contains a small amount of mangrove, probably all that is found in the atoll. There is a small island (at high tide) near the western edge of the inlet. At low tide the deeper part forms a small brackish lake.

The wide northern end of Ngariungs is largely covered with rather heavy jungle, including some large trees of a few feet in diameter with somewhat buttressed trunks.

Among these were many vines, including Epipremnum pinnatum and Mucuna sp., also birds nest ferns, Asplenium nidus. Not far from the northeast corner there

are some small clearings in the jungle where some false taro, tapioca and squash vines still grow, though poorly tended. At the extreme north end of the islet there is a small tin-roofed shelter and an oil drum which collects the rain water which runs down the trunk of a Pandanus plant. In the shady jungle nests of megapode birds are common, some of them measuring 25 feet in diameter and five feet in height. They consist of sand and bits of worn coral from the jungle floor, after the vegetable matter which incubated the eggs has rotted away. One or two old worn down nests were also seen on the main island. The young birds emerged from one nest on Ngariungs between visits two days apart, in September. The birds were frequently heard in the dense jungle. Other land birds seen were kingfishers (Halcyon chloris teraokai) and the morning bird (Colluricincla tenebrosa). Several monitor lizards were seen.

The part of Ngariungs south of the inlet has fewer tall trees, but is rather densely covered with second growth forest. Coconut palms were limited in number to only about 330 grown palms, of which quite a number have been killed and consumed by the coconut beetle, which reached this islet first, of Kayangel, about 1946. The largest were just west of the inlet, and are all lost. The jungle has grown up around most of the remaining palms, which are seriously affected by the beetle. This islet was inhabited by American troops just before and after the close of the war.

The third islet, Ngarapalas, is again much smaller than Ngariungs, and is separated from it by much more than its own length. It is broad at the north end, where it is largely covered with dense scrub jungle of rather short trees, except on the west side which is partly bare except for rows of coconut palms up to ten years in age. This western part consists of coral gravel. There are some taller coconut palms near the center of the islet and around the cove on the east side. The eastern part of the tapering southern portion of the islet has some low scrub. The northern part of the east shore is of rough coral limestone with loose coral rocks washed up. The southern part of the east coast is sandy, and here high on the beach a large sea-turtle nest was found containing at least 100 eggs. Off of this beach is a large platform of rough coral rock, somewhat uneven in nature, which is largely exposed at low tide and which connects with the last islet.

The southernmost islet, Gorak, is much smaller than Ngarapalas, and close to it. Most of its northeastern half is flat and almost barren, with just a few shrubs and young coconut palms. Some terns and other sea birds lay their eggs among the coral pebbles and drift wood on this open area. Triumfetta procumbens and some low-lying prickly herbaceous vines grow on this portion. Scaevola and a few other plants are also present. The remainder of the islet, roughly rounded, bears about 55 coconut palms mostly about 40 feet in height, besides some younger ones, some of which extend north a short distance along the edge of the beach on the west side. Just a few other shrubs and small trees flank the coconut palms, or are mixed with them. The east and south shores of the islet are covered with piled up coral rocks. Some floating logs from elsewhere have been washed ashore by storms, even to the center of the islet, which is less than 100 yards across. From Ngariungs, Ngarapalas appears to be several times as long as Gorak because it is nearer and more fully covered with tall vegetation. Ngarapalas islet is owned by the chief of Kayangel, and Gorak islet by the second chief.

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The northeastern end of Gorak Islet, the southwestern end of Ngarapalas islet, and to a lesser extent the northwestern corner and south end of Ngariungs appear to have been added to since earlier maps were made, as those portions consist largely of coral rocks, rubble and sand. In the case of the former two the material is raised approximately to the general level of the islands. New vegetation is taking root on those situations and to some extent on the point extending towards the sandflats on the northwestern corner of Ngariungs, where the sand is also raised fairly high. The plants involved are mostly Barringtonia, Cocos and some creeping vines including Triumfetta. The common moth Utetheisa was extremely abundant on Gorak islet, presumably breeding on Messerschmidia.

The soils of Kayangel consist largely of coarse loamy sand, sometimes mixed with coral gravel, but in some parts, such as much of central Ngajangel it consists largely of gravel, with or without a thin layer of sand or loamy sand on the surface.

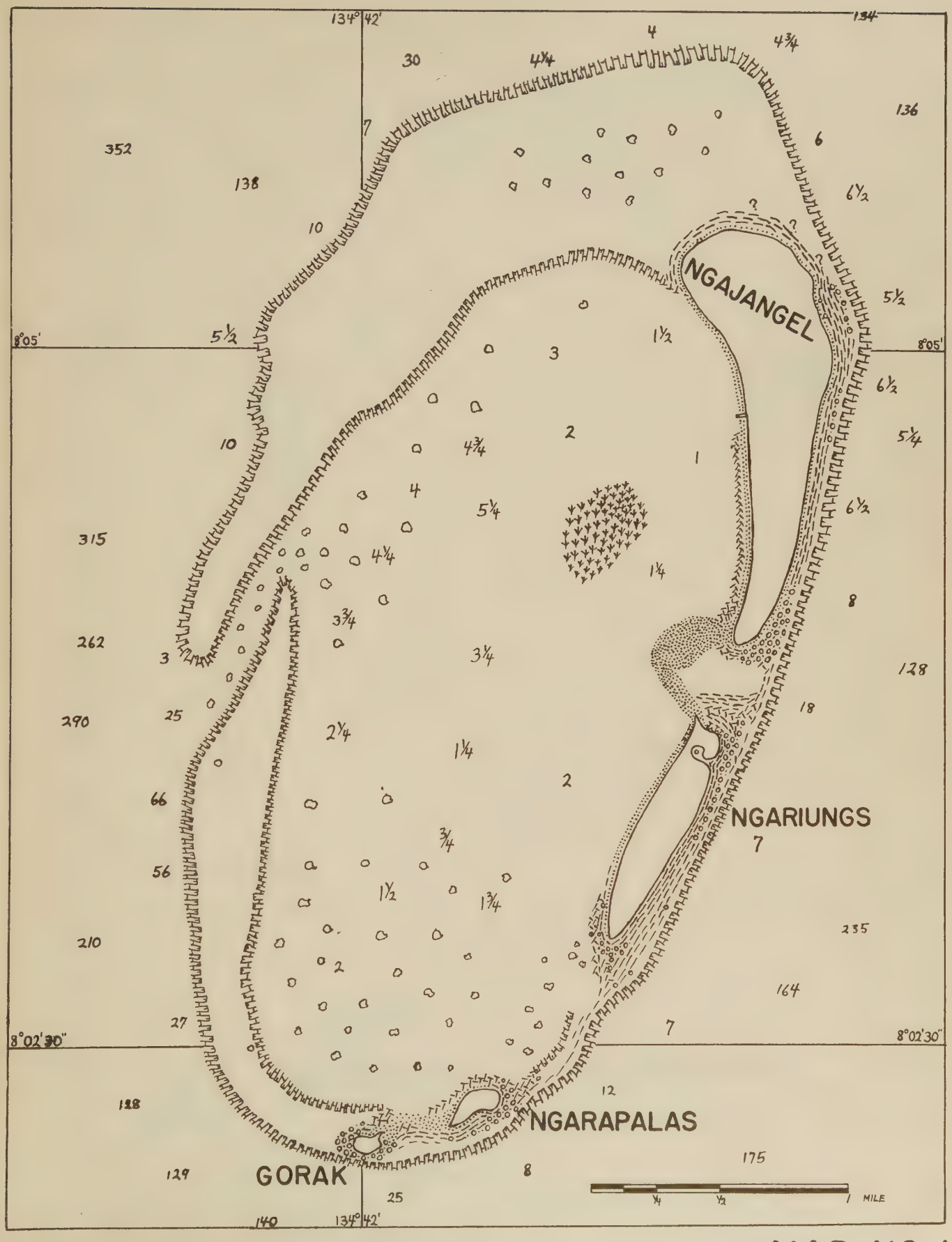
A small rat (Rattus exulans?) is common around stumps or in the small grassy areas between coconut palms on the main island. Examination of four stomachs showed that they fed almost entirely on copra, probably from the drying sheds along the lagoon beach.

The above notes are based on visits to Kayangel Atoll during July 24-25, September 13-17 and November 24-25, 1951. The northeastern corner of the main island was not seen, and its northern tip was seen only at high tide. On the two maps the outer reef outline and outline of main island were taken from A.M.S. W752 (1942, 1943) and the soundings from 64th Eng. Top. Bn. USAFCPBC No. 1023 (1944) based on H. O. Chart 6074.

LEGEND FOR MAPS

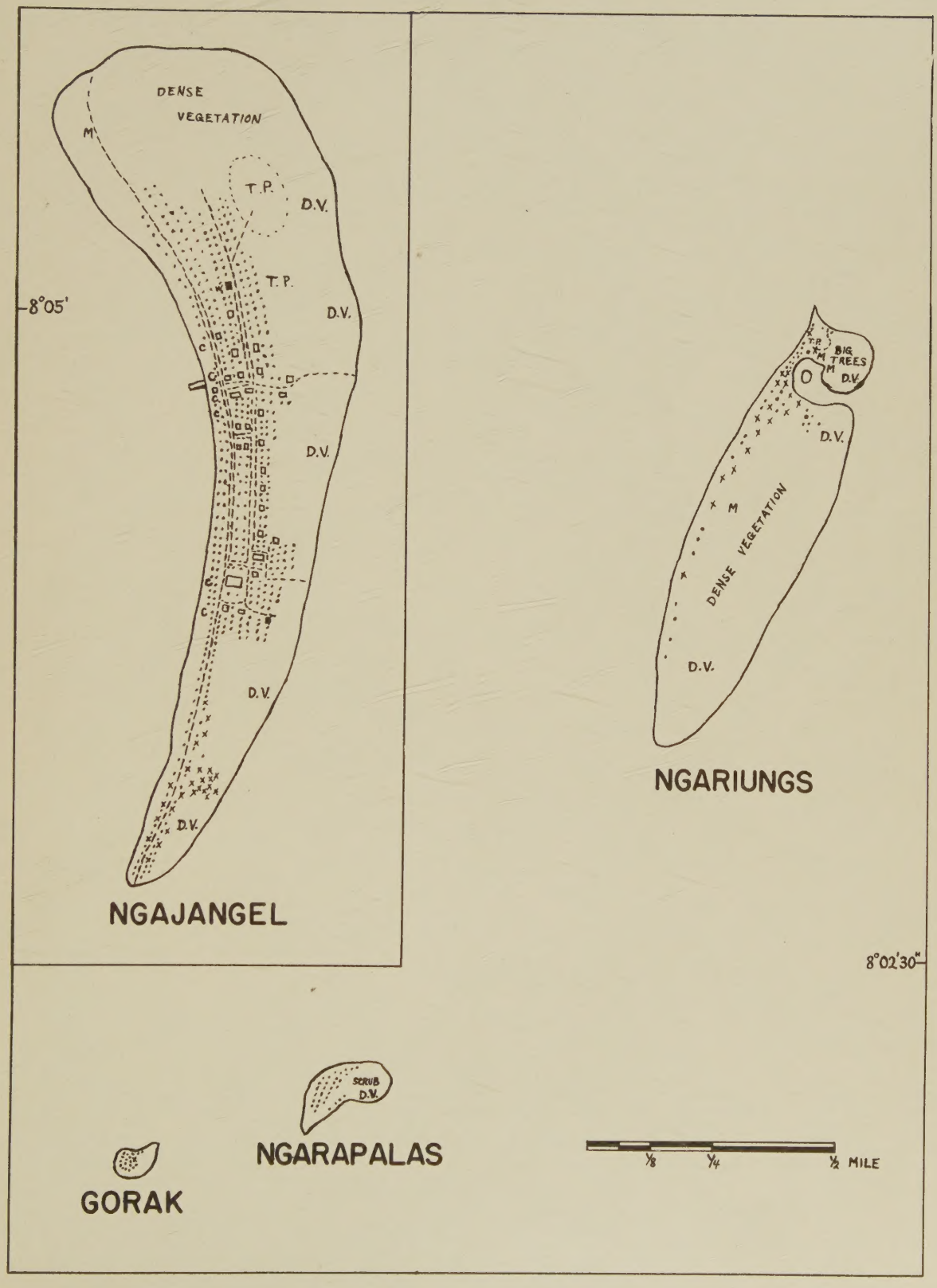
	Coral heads
	Edge of coral reef
	Staghorn coral
	Solid reef limestone
1 3/4	Soundings in fathoms
	Sand exposed at low tide
	Coral gravel
	Loose coral rocks
	Beach sandstone
D. V.	Dense vegetation (semi-natural)
T. P.	Taro pits
M.	Megapode nests
: : :	Coconut palms
× ×	Coconut palms killed by coconut rhinoceros beetle
	Well
	Houses, a-bais or school
----	Paths
====	Main avenues

KAYANGEL ATOLL



MAP NO. I

ISLETS OF KAYANGEL ATOLL



MAP NO. 2